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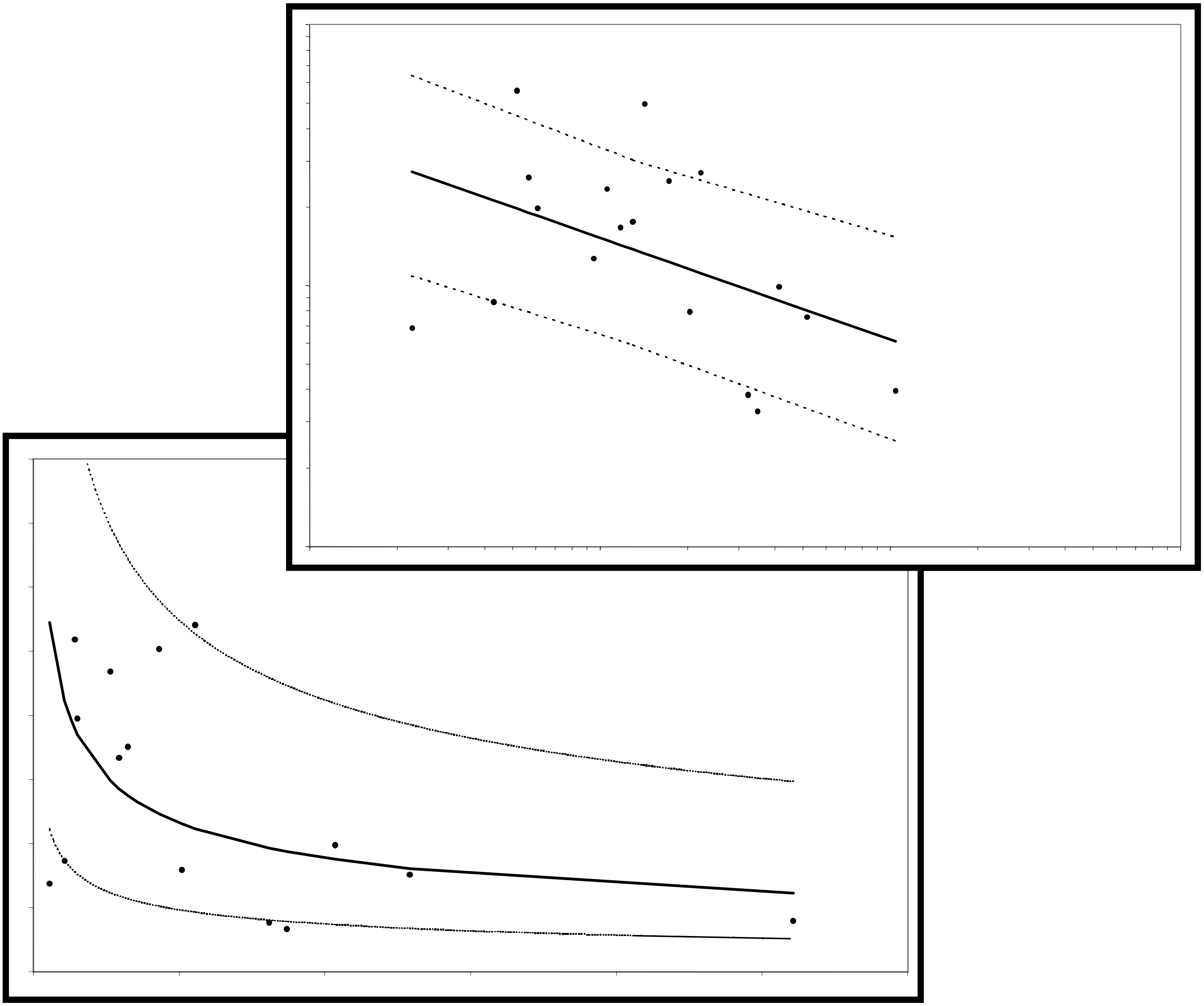
Remediation Technology Cost Compendium – Year 2000



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Remediation Technology Cost Compendium – Year 2000

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460

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FOREWORD

Although there has been progress over the years in cleaning up hazardous waste sites, relatively little data are available about the costs of actual field applications of remediation technologies. The United States Environmental Protection Agency (EPA) believes these historical costs are of value to potential future users of these technologies.

The technologies selected for inclusion in this compendium are commonly applied for on-site remediation and have the most data available. Costs were obtained exclusively from federal agency sources, many of which are part of an ongoing effort by the Federal Remediation Technologies Roundtable (FRTR) to document cost and performance case studies.

Curves for specific technologies were developed to illustrate the correlations between unit costs and quantity of media treated or mass of contaminant removed. During the analysis of the cost data and development of the curves, consideration was given to what constitutes an adequate fit or correlation, how to portray variations, and how to prevent misinterpretation of the cost curves. There were concerns about whether, in some cases, the data adequately fit the curves and whether the data were consistent with the assumed distribution. Furthermore, there was concern that additional independent variables may contribute to the relatively large variability in the data.

While additional data would undoubtably help to better define the cost of remediation technologies, available data are deemed sufficient to begin showing patterns in unit cost for four technologies. This report does not seek to provide predictive cost models but rather to illustrate trends that can be derived at this time from available information. Incomplete as this information may be, it is of value to those who have various interests in the application of these technologies. For this compendium, the procedures used to analyze each technology have been thoroughly documented, and important considerations related to use of the document have been identified. EPA plans to update this compendium as additional cost data become available.

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EXECUTIVE SUMMARY

The United States Environmental Protection Agency (EPA) has prepared this cost compendium to capture current information about the costs of the following six remediation technologies: (1) bioremediation; (2) thermal desorption; (3) soil vapor extraction (SVE); (4) on-site incineration; (5) groundwater pump-and-treat systems; and (6) permeable reactive barriers (PRBs). These technologies have been used during the past several years to clean up contaminated media through federal and state remediation programs, including those implemented under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). Information about the costs of specific applications of remediation technologies will help facilitate comparisons of options and improve remedy selection. In addition, the information provides a baseline that can be used in evaluating innovative and conventional technologies and can be used to help assess other sources of cost data, such as those provided by technology vendors and others.

Cost data were obtained from federal agency sources, including case studies and reports prepared by the Federal Remediation Technologies Roundtable (FRTR)[1], the U.S. Department of Energy's (DOE) Los Alamos National Laboratory; the U.S. Army Corps of Engineers (USACE) Hazardous, Toxic, and Radioactive Waste Center for Expertise; and the U.S. Air Force Center for Environmental Excellence (AFCEE). Those sources provided cost data for approximately 150 projects. The data were sufficient to begin identifying patterns in costs of several technologies. However, additional cost data for remediation technologies, collected through the use of standard procedures, will help to further increase understanding of the factors affecting the cost of technology applications.

One effort underway to improve the availability of cost data is the FRTR cost and performance initiative. Since 1995, the FRTR has been working to document remedial projects and to make such information more readily available. To date, the agencies of the FRTR have prepared more than 270 case studies. These case studies were the source of much of the data used in this compendium. The goals of the FRTR in providing cost information about specific applications of remedial technologies are to:

- Increase the availability of standard cost data to facilitate comparison and help improve remedy selection
- Provide a baseline of information about conventional technologies that can be used as a benchmark in evaluating innovative technologies
- Provide a system for tracking data on changes over time in the costs of specific remedial activities

The FRTR continues to gather data on costs and to add those data to its web site at *<http://www.frtr.gov>*. Additional information about the FRTR and its recommended procedures for documenting case studies is included in the FRTR's *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (the guide), EPA 542-B-98-007, October 1998, which is available through the FRTR web site.

Another major source of data for this compendium was the report *Bioventing Performance and Cost Results from Multiple Air Force Test Sites, Technology Demonstration, Final Technical Memorandum* prepared by the AFCEE. This Air Force report presents cost data on 45 bioventing projects and was the major source of data on bioventing in this document. The data from the Air Force report are considered unique in the field because they represent a

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[1] The FRTR includes members representing the United States Department of Defense (including the U.S. Army, U.S. Navy, and U.S. Air Force), the United States Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and EPA and maintains a web site at <*http://www.frtr.gov*>. Current members who are responsible for working with the FRTR and coordinating the collection of information are listed in Appendix C to this report.

comprehensive effort to collect costs through use of standard procedures. The report is available at <*http://www.afcee.brooks.af.mil/er/ert/costperf.htm*>

The key findings of this compendium are presented below:

Overall Findings

Correlations between unit costs and quantity treated or mass removed were evident for four of the six technologies - bioventing, thermal desorption, SVE, and pump-and-treat systems. Cost curves were developed to show the correlation between unit cost and quantity of material treated for all four technologies, with the unit costs for pump-and-treat systems shown in terms of both unit capital cost and unit operating cost. For SVE, a cost curve that shows unit cost compared with mass of contaminant removed was developed, in addition to the cost curve for unit cost compared with quantity treated.

Economies of scale were observed for the four technologies where unit costs decreased as larger quantities were treated. The higher unit costs for lower quantities are attributed to the effect of fixed costs (the baseline costs of constructing and installing the technology). For the three soil treatment technologies with cost curves (bioventing, thermal desorption, and SVE), the unit costs tended to increase rapidly and show greater variability for treatment of less than 10,000 to 20,000 cubic yards of soil.

Costs of technology applications are site-specific and are affected by many factors. The relatively high variability indicates that a number of factors potentially impact the cost of a technology application, that those factors vary by technology, and that the impact of those factors is site-specific. Examples of other factors include properties of the contaminant present and characteristics of the matrix treated, concentrations of contaminants, and distribution of contamination in the subsurface; type and properties of the soil; and hydrogeology of the site, including characteristics of the aquifer.

Several additional factors affect all technologies - Other factors that affect costs for all remediation technologies include market forces, such as supply and demand; the state of development of the technology; and regulatory requirements, including federal, state and local requirements. The specific impact of such factors on project costs are difficult to quantify because they may vary by location and change over time.

Technology-Specific Findings

Among the four technologies for which cost curves were developed, bioventing had the best correlation between unit cost and quantity of soil treated. These sites tended to have similar characteristics and the relatively high correlation most likely reflects the standard procedures used by the Air Force in collecting the data. Unit costs decreased from $10 to $50 per cubic yard for projects treating up to 10,000 cubic yards of soil to less than $5 per cubic yard for projects treating relatively larger quantities of soil.

For other types of bioremediation, no quantitative correlation between unit cost and quantity of soil or groundwater treated was observed. Cost data for various types of bioremediation projects (*in situ* soil, *ex situ* soil, and *in situ* groundwater) were limited. While no quantitative correlation was evident, unit costs for bioremediation potentially are affected by other factors including soil type and aquifer chemistry, site hydrogeology, type and quantity of amendments used, and type and extent of contamination.

For thermal desorption, the unit cost was affected by the types of contaminants treated, and a correlation between unit cost and quantity of soil treated was observed for projects where polychlorinated biphenyls (PCBs) were not present. Projects where PCBs were present as a contaminant tended to have higher unit costs than projects where PCBs were not present. A difference in the emissions control technologies for these two types of projects likely contributed to the difference in cost. Projects treating PCBs tended to include more complex technologies such as oxidation as part of the treatment for recovered scrubber water, and involved additional emissions monitoring.

Because of their different characteristics, those projects were analyzed separately from projects where PCBs were not present.

For projects where PCBs were not present, unit costs decreased from $100 to $250 per ton for projects treating up to 20,000 tons of soil to less than $50 per ton for projects treating relatively larger quantities of soil. However, the cost curve contains a wide confidence interval. For projects where PCBs were present, data were not sufficient to support a quantitative analysis of unit cost compared with quantity treated. No correlations between unit cost and other factors, such as soil properties and treatment temperature, were identified.

For SVE, a correlation between unit cost and quantity of soil treated and unit cost and mass of contaminant removed was observed. Unit cost decreased from $60 to nearly $350 per cubic yard for projects treating less than 10,000 cubic yards of soil to less than $5 per cubic yard for projects treating relatively larger quantities of soil. In addition, unit cost decreased from $300 to approximately $800 per pound for projects where up to 3,000 pounds of contaminant mass were removed to less than $15 per pound for projects where larger quantities were removed.

For on-site incineration, no correlation between unit cost and quantity of material treated was observed. A quantitative analysis of unit cost compared with tons of soil treated was performed for five incineration projects that treated solid media (such as soil, sludge, sediment, and debris). While no quantitative correlation was evident, unit costs for incineration potentially are affected by other factors including soil type and characteristics of the matrix, type and concentration of contaminants, and maintenance needs.

For groundwater pump-and-treat systems, a correlation between unit cost and quantity of groundwater treated was observed for both the unit capital cost and the unit average annual operating cost. Unit capital cost decreased from $60 to approximately $700 per 1,000 gallons per year for projects treating up to 30 million gallons of groundwater per year to less than $20 per 1,000 gallons per year for projects treating relatively larger quantities of groundwater. Unit average annual operating cost decreased from $10 to $120 per 1,000 gallons per year for projects treating less than 20 million gallons of groundwater per year to less than $5 per 1,000 gallons per year for projects treating larger quantities of groundwater.

For PRBs, data were not available to perform a quantitative analysis of unit cost compared with quantity of groundwater treated because of a lack of information about quantity treated. Capital costs were available for 16 PRB projects, and annual operating costs were available for two projects. However, the case studies for PRBs do not provide information about anticipated longevity of the project or about the quantity of groundwater treated or the mass of contaminant removed and do not report unit costs or information needed to calculate unit costs. While no correlations could be performed, unit costs for PRBs potentially are affected by other factors including properties of the contaminants and extent of contamination, the need for source control, the hydrogeologic setting, and the geochemistry of the aquifer.

Important Considerations About This Cost Compendium

- The compendium provides a compilation of historical cost data about six remediation technologies for use by site managers, engineers, decision makers, and other parties interested in assessing remedies. Cost data were taken from the referenced sources and were not subjected to independent verification or validation. The curves are a best-fit based on the available data and are intended to be used for illustrative purposes. The user should not assume that the curves can be used in predicting the cost of future applications because of the effects of site-specific factors.

- The curves may be useful early in the remedy planning process when a “top-down” analysis of technology costs is performed for general comparative purposes. Later in the implementation process, when more detailed "bottom-up" cost analyses may be performed, other tools, such as the Air Force's Remedial Action Cost Engineering & Requirements (RACER) and the Navy's Cost to Complete (CTC) systems, may be more appropriate for projecting the cost of future applications.

- The approach to the cost analysis was designed to be consistent with acceptable statistical practices. All cost data used in the analysis first were adjusted for time and location to a common basis. The approach for developing the cost curves, using a reverse exponential model, was tested on Air Force bioventing cost data for 45 projects. Those data provided the largest number of technology applications having similar characteristics and represented a comprehensive effort to collect costs at a number of sites through standard procedures. While this approach provided a reasonable fit for the Air Force data, it is important to note that the statistical fit for some other data was not good. Some concerns were expressed about the statistical methodology used for this analysis, including the adequacy of the fits and correlations, the limited number of data points, and the effects of other independent variables. While the data and analysis in this report do not support use of the cost curves as predictive models, they do illustrate trends in unit costs which may be useful as part of a broad assessment of technologies.

- The cost curves in this compendium are based solely on cost data provided in the case studies and other information sources. Projects were identified for inclusion in this analysis on the basis of availability of information and were not intended to represent a cross-section of all projects for each technology. All available projects and data were compiled, and the analysis does not exclude any data as statistical outliers.

- While this compendium focuses on unit cost, there are other methods of examining costs when comparing technologies. Such methods include total cost, total capital, or total operating cost, or the cost of a technology compared with the level of risk reduction or other factors.

1.0 INTRODUCTION

The United States Environmental Protection Agency (EPA) has prepared this *Remediation Technology Cost Compendium - Year 2000* (compendium) to provide site managers, technology users, technology developers, and other interested parties with a better understanding of the costs of specific remedial technologies and the factors that affect those costs. The remediation technology market is now at a point at which sufficient data are available from federal agencies to begin to identify trends in the costs of selected technologies. This compendium provides information about the costs of the following six on-site remedial technologies for cleanup of sites with contaminated media:

- Bioremediation
- Thermal desorption
- Soil vapor extraction (SVE)
- On-site incineration
- Groundwater pump-and-treat systems
- Permeable reactive barriers (PRBs)

Those technologies were selected for this analysis because they are commonly used for on-site remediation of hazardous waste sites and because it was believed that the most cost data were available for them from the identified federal agency sources.

Cost data for this compendium were obtained from federal agency sources, including case studies and reports prepared by the Federal Remediation Technologies Roundtable (FRTR), the U.S. Air Force Center for Environmental Excellence (AFCEE); the U.S. Department of Energy's (DOE) Los Alamos National Laboratory (LANL); EPA's National Risk Management Research Laboratory (NRML); and the U.S. Army Corps of Engineers (USACE) Hazardous, Toxic, and Radioactive Waste Center for Expertise. Brief descriptions of those sources are presented below.

FRTR: FRTR case studies present information from more than 200 case study reports about remedial technology projects, including cost data for the six remediation technologies of interest for this compendium. Each case study provides information about the site background, technology design and performance, cost, and lessons learned. Cost data generally were reported in the format provided in the FRTR's Guide to Documenting and Managing Cost and Performance Information for Remediation Projects (the guide), with the level of detail of the cost data varying by case study. Case studies are available at the FRTR web site at *<http://www.frtr.gov/cost/>*.

AFCEE: AFCEE prepared the report *Bioventing Performance and Cost Results from Multiple Air Force Test Sites*, June 1996, about 45 bioventing projects that were performed at Air Force bases throughout the country. For each project, information is provided about site name, location, total cost of bioventing and volume of soil treated. A standard protocol was used in collecting the cost data.

DOE LANL: The report *A Compendium of Cost Data for Environmental Remediation Technologies,* Los Alamos National Laboratory (LANL), LA-UR-96-2205, August 1996 presents summary information about 250 commercial or pilot-scale remedial projects, including actual costs, site characteristics, and comments about the project. Cost data were provided by a variety of sources (including FRTR case studies) and vary in level of detail. The report is available at *<http://www.lanl.gov/orgs/d/d4/enviro/etcap>*.

EPA NRML: Bioremediation in the Field Search System (BFSS), Version 2.1 is a database of information about waste sites in the U. S. and Canada where bioremediation is being tested or implemented or has been completed. The database contains information about 450 full-scale bioremediation efforts and treatability and feasibility studies. BFSS is available at *<http://clu-in.org/PRODUCTS/MOREINFO/Bfss.htm>*.

USACE: The report *Cost Data for Innovative Treatment Technologies*, Internal Draft USACE, July 1997, presents information about the cost of selected technology applications, drawn from data available in public sources and from personal communications with site managers. In addition, USACE identified key factors at the sites that are related to project costs.

General Methodology

The general methodology used in analyzing cost data for the six remediation technologies is described below. Any variations from the approach are discussed in the section for each technology.

1. *Identify Projects for Which Cost Data Are Available for Each Technology*

The available information sources were reviewed to identify projects for which cost data are available for the six technologies. Only technology applications that were uniquely identified by site name and location and that primarily used a single technology were included.

2. *Identify Projects for Which Fully Defined Costs Are Available for Each Technology*

For each project identified for the six remediation technologies, available information was evaluated to determine whether "fully defined" cost data were available. Cost data were considered fully defined if the data met the following criteria:

- The total cost directly associated with the treatment technology application (capital and operation and maintenance [O&M]) must be provided and differentiated clearly from other project costs that are not directly associated with the treatment application, as defined in the guide. The treatment technology cost may be provided as (1) a total cost for the application, (2) total capital and total O&M, or (3) a more detailed breakdown of individual cost elements for total capital and total O&M costs. For *ex situ* technologies, costs for activities such as excavation and disposal of residuals were not included in the total cost, as described in the guide.

- The cost data must be based on the actual application (historical) rather than on projected (future) activities. The historical costs may be provided as the actual or estimated costs of treatment-related activities that have been performed. Projections of full-scale costs from demonstration-scale projects were not considered.

- To allow the calculation of a unit cost, information must be provided about the total quantity of material treated or mass of contaminant removed. The information may be provided for the technology application (for completed projects) or through a specified period of operation (for ongoing projects).

- The cost data must be obtained from a federal agency source.

Cost data were obtained directly from the cited sources, and no independent verification of costs was performed. All costs presented in this compendium have been rounded to three significant digits.

3. *Normalize the Total Cost Projects with Fully Defined Cost Data for Time and Location*

Total costs for technology applications were standardized to make them comparable, with adjustments made for both time and location. The following methods were used to make those adjustments.

- **Inflation Adjustment:** The total cost of each application was adjusted to year 1999 dollars by multiplying the unadjusted total cost by an inflation factor for the year in which the costs were incurred. The inflation factor used for the analysis was obtained from the Construction Cost Index published by *Engineering News Record*. The most current year for which an annual average inflation adjustment factor was available at the time this compendium was prepared was 1999. For time adjustment of capital costs, the inflation adjustment factor for the actual year in which the costs were incurred was used. For time adjustment of annual operating costs, the inflation adjustment factor for the median year of all years over which the costs were incurred was used. The Construction Cost Index is available at *<http://www.enr.com/cost/costcci.asp>*.

- **Location Adjustment:** The total cost of each application was adjusted for location by multiplying the costs provided for each site by an Area Cost Factor Index published by USACE in *PAX Newsletter*, No. 3.2.1, dated March 31, 1999 and available on the USACE web site at *<http://www.hq.usace.army.mil/cemp/e/es/pax/paxtoc.htm>*.

4. *Determine Unit Costs for Projects with Fully Defined Cost Data*

Following adjustments for time and location, the unit cost of a technology application was calculated by dividing the adjusted total cost of the treatment technology application and the quantity of material treated or contaminant removed, as appropriate.

5. *Perform a Cost Analysis by Technology*

An analysis of unit cost versus quantity treated was performed to determine whether a correlation was evident. The analysis was performed for technologies for which fully defined cost data were available for five or more projects having similar characteristics. In addition, cost data were evaluated to determine whether correlations were evident for other factors that potentially affect the cost of a technology application, including type of contaminants treated, types and characteristics of media treated, and technology design parameters.

If a correlation was evident, cost curves were developed, using a reverse exponential linear fit on the data, as described below (Appendix B presents additional information about statistical calculations and alternative confidence interval calculations):

1. For each technology, the natural logarithm of the data on unit cost and quantity treated data was calculated. The transformation was based on the assumption that the data would fit a reverse exponential model, which typically is used to model unit cost data.

2. For each technology, a linear regression of log-transformed data was performed to calculate the best-fit of the data. Statistical parameters, such as goodness of fit and coefficient of determination were calculated for each plot.

3. Confidence intervals (68 and 95 percent, corresponding to one and two standard deviations, respectively) were calculated for each fit.

4. The actual data, best-fit line, and confidence intervals (for 68 percent) were plotted on a logarithmic-scale (base 10) graph. In addition, a decimal-scale plot was prepared that showed the best-fit line and 68 percent confidence internals to illustrate a specific range of unit costs and quantity treated (or mass removed) for an individual technology. Users of the cost curves should note that the labels and scales on the graphs vary by technology.

In addition, other factors that potentially affect costs, such as contaminants treated, types and characteristics of media treated, and technology design parameters, were considered, drawing on information provided in the case studies and available references. For each technology, that information is presented in narrative format.

Organization of the Report

This report includes six sections, each of which describes the cost analysis for one of the six technologies - bioremediation (Section 2), thermal desorption (Section 3), SVE (Section 4), on-site incineration (Section 5), pump-and-treat (Section 6), and PRBs (Section 7). Each of the sections includes a brief description of the technology, a discussion of the methodology used in the cost analysis, and the results of the cost analysis. The results subsection includes the results of quantitative analyses (cost curves), when adequate correlations were evident, and qualitative information about factors that potentially impact the costs of a technology application. Section 8 is a list of references used in preparing this report. Appendix A of this report presents a summary of information about costs of off-site disposal of wastes. The summary is based on information prepared by USACE, *Report on Treatment, Storage, and Disposal Facilities (TSDFs) for Hazardous, Toxic, and Radioactive Waste*, and is provided for purposes of comparison. Appendix B provides additional information about the development of cost curves, and Appendix C presents a list of active members of the FRTR cost and performance work group.

2.0 BIOREMEDIATION

Bioremediation is a remedial technology that uses biological processes to destroy or transform contaminants. Bioremediation may be intrinsic (natural) or enhanced (engineered) by adding nutrients, electron donors or acceptors, or microbes to soil or groundwater. This section presents a summary of data obtained from case studies of on-site bioremediation projects that employ engineered systems and the results of the analysis of those data.

Methodology for Cost Analysis for Bioremediation Projects

As Exhibit 2-1 shows, 69 bioremediation case studies addressing 61 individual projects[2] were identified from the available information sources. Bioremediation projects were identified through application of the criteria discussed in Section 1 and the following two technology-specific criteria:

- The application must be identified in the information source as *in situ* bioremediation of groundwater, *in situ* bioremediation of soil, or *ex situ* bioremediation of soil.[3]
- The application must be primarily a bioremediation project and must not have a significant non-bioremediation component. Therefore, applications that used bioremediation in combination with another technology, such as SVE or groundwater pump-and-treat technologies were not included.

Capital and O&M costs were obtained from the case studies, along with data needed to calculate unit costs, such as volume of material treated. Of the 61 projects, fully defined cost data, as described in Section 1, were determined to be available for 22. Exhibits 2-2 and 2-3 summarize the total number of projects and projects with fully defined cost data were available by project type and by contaminant type, respectively.

Exhibit 2-1. Bioremediation Case Studies - Sources

Source	Number of Case Studies
FRTR bioremediation case studies (volumes 1 [1995], 5 [1997], and 7 [1998] and CD-ROM [2000]). Available at *http://www.frtr.gov/cost*.	27
A Compendium of Cost Data for Environmental Remediation Technologies, LANL, LA-UR-96-2205, August 1996. Available at *http://www.lanl.gov/orgs/d/d4/enviro/etcap*.	32
Case studies presented in *Cost Data for Innovative Treatment Technologies*, USACE, July 1997.	7
Bioremediation in the Field Search System, Version 2.1. Available at *http://clu-in.org/PRODUCTS/MOREINFO/Bfss.htm*.	3

Exhibit 2-2. Bioremediation Projects by Project Type (Total Projects/Projects for Which Fully Defined Cost Data Are Available)

Project Type	Total Projects	Projects with Fully Defined Cost Data
Ex Situ Bioremediation (Soil)	31	13
In Situ Bioremediation (Soil)	11	3
In Situ Bioremediation (Groundwater)	19	6
TOTAL	**61**	**22**

Exhibit 2-4, organized by bioremediation project type, presents summary information about the 22 projects with fully defined cost data, including name, location, contaminants, and cost information.

In addition to the bioremediation projects discussed in Exhibit 2-4, 45 bioventing projects were identified in a report prepared by the AFCEE.

Exhibit 2-3. Bioremediation Projects by Contaminant Type (Total Projects/Projects Having Fully-Defined Cost Data)

Project Type	Contaminated Type							
	VOCs			SVOCs				
	BTEX	cVOCs	Other	PAHs	PCBs	Pest/Herb	Other	PHCs
Ex Situ Bioremediation (Soil)	8/6	2/2	2/2	9/6	2/1	1/0	7/4	3/0
In Situ Bioremediation (Soil)	5/2	2/0	1/0	0/0	0/0	0/0	1/0	0/0
In Situ Bioremediation (Groundwater)	2/0	10/5	0/0	0/0	0/0	0/0	0/0	0/0

Notes:

Several projects address more than one contaminant

BTEX = Benzene, toluene, ethylbenzene, and xylenes
cVOC = Chlorinated volatile organic compound
Other SVOC = Other semivolatile organic compound
Other VOC = Other volatile organic compound (for example, ketones)
PAH = Polycyclic aromatic hydrocarbon
PCB = Polychlorinated biphenyl
Pest/Herb = Pesticides and herbicides
PHC = Petroleum hydrocarbons
SVOC = Semivolatile organic compound
VOC = Volatile organic compound

Technology Transfer Division entitled *Bioventing Performance and Cost Results from Multiple Air Force Test Sites, Technology Demonstration, Final Technical Memorandum*, June 1996. Cost information for the 45 bioventing projects included total cost and quantity treated. Because the data for the Air Force report represented a comprehensive effort to collect cost data by standard procedures, the data were considered to be unique in the field and, therefore, were analyzed separately.

Results of Analysis of 22 Bioremediation Projects with Fully Defined Cost Data

Unit Cost Versus Quantity Treated

The 22 projects with fully defined cost data were reviewed to identify projects that exhibited similar characteristics (project type and contaminant type). Five or more projects were identified for the following groups:

- *Ex situ* bioremediation (soil), with BTEX as a contaminant (6 sites)
- *Ex situ* bioremediation (soil), with PAHs as a contaminant (6 sites)
- *In situ* bioremediation of groundwater, with chlorinated solvents as a contaminant (5 sites)

The costs for the projects in each of the three groups were evaluated to determine whether any correlations in unit cost versus quantity of soil or groundwater treated were evident. No correlation between unit cost and quantity of soil or groundwater treated was evident for any of the groups.

Other Factors

Potential correlations between unit cost and other factors, such as soil type, moisture content, and types of amendments used, were considered for the projects in each group, but none was identified. While no quantitative correlations for those factors were evident, the following qualitative information about potential factors affecting the design and operation of bioremediation systems was provided in the case studies and in the EPA report *Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents*, July 2000. The specific effects of those and other factors on the cost of a bioremediation system are site-specific.

Soil type and aquifer chemistry: For *in situ* bioremediation, the porosity, organic content, and moisture content of the soil affect the flow rate of fluids and are factors in determining the delivery method for additives and how well the additives disperse in the subsurface. Parameters such as oxygen content, pH, redox potential,

Exhibit 2-4. Summary of Bioremediation Projects with Fully Defined Cost Data
(Page 1 of 3)

Site Name	State	Cleanup Under	Status	Contaminants	Start Year	Area Cost Factor	Technology Cost ($)* (Source)	Volume Treated (yd^3)	Unit Cost ($\$/yd^3$)	Comments
Ex situ* Bioremediation (Soil)*										
Bonneville Power Administration Superfund Site	WA	Superfund	FS Complete	PAHs, Other SVOCs	1995	1.07	1,280,000 (1)	1,048	1,220	Included extensive technology demonstration activities
Brown Wood Preserving Superfund Site	FL	Superfund	FS Complete	PAHs	1989	0.87	635,000 (1)	8,100	78.4	Constructed lined treatment system; moderate initial contaminant concentrations
Dubose Oil Products Co. Superfund Site	FL	Superfund	FS Complete	BTEX, cVOCs, Other SVOCs, Other VOCs	1993	0.87	4,990,000 (1)	13,137	380	Treatment system constructed in building, including leachate collection, inoculant generation, vacuum extractions, and wastewater treatment
Fort Greely UST Soil Piles	AK	Other	FS Complete	BTEX, PHC	1994	1.60	749,000 (1,2)	9,800	76.4	O&M only in summer months; no liner
Fort Wainwright, North Post Site Soil Remediation	AK	Other	FS Complete	BTEX	1993	1.60	433,000 (1)	4,240	102	Remediation technology costs only; activities included liner construction, drainage, tilling, and addition of nutrients
French Limited Superfund Site	TX	Superfund	FS Complete	cVOCs, PAHs, Other SVOCs, Other VOCs, PCBs	1992	0.82	26,810,000 (1)	300,000	89.4	Extremely large volume; remediation conducted *ex situ*, but in place
Glasgow Air Force Base UST Removal	MT	Other	FS Complete	PHC	1994	1.14	60,000 (2)	4,800	12.5	Application primarily consisted of soil tilling
Havre Air Force Station, Remove Abandoned USTs	MT	Other	FS Complete	BTEX	1992	1.14	48,700 (2)	1,786	27.3	Application primarily consisted of soil plowing and tilling
Lowry AFB	CO	Other	FS Ongoing	BTEX, PHC	1992	1.03	130,000 (1)	5,400	24.1	Conducted on plastic sheeting, nutrients added once and aerated; interim costs
Matagora Island Air Force Base	TX	Other	FS Complete	BTEX	1992	0.82	77,600 (2)	500	155	Cost of entire project including excavation, treatment, and monitoring

Exhibit 2-4. Summary of Bioremediation Projects with Fully-Defined Cost Data
(Page 2 of 3)

Site Name	State	Cleanup Under	Status	Contaminants	Start Year	Area Cost Factor	Technology Cost ($)* (Source)	Volume Treated (yd^3)	Unit Cost ($/yd^3)	Comments
Scott Lumber Company Superfund Site	MO	Superfund	FS Complete	PAHs	1990	0.96	6,580,000 (1)	10,641	618	Constructed lined treatment area, irrigation and drainage system, and addition of nutrient and culture
Southeastern Wood Preserving Superfund Site, OU 1	MS	Superfund	FS Complete	PAHs	1991	0.87	2,550,000 (1)	10,500	243	Bioreactor system constructed; high initial contaminant concentrations; extensive pretreatment
Umatilla Army Depot Activity (FS)	OR	Other	FS Complete	Other SVOCs	1994	1.15	5,260,000 (1)	10,969	479	Composting conducted in building; one of first biotreatment projects for soil contaminated with explosives; maintained high moisture content
***In Situ* Bioremediation (Soil)**										
Dover AFB, Area 6	DE	Superfund	DS Complete	cVOCs, Heavy metals	1996	1.02	551,000 (1)	1,667	331	Direct injection of air and propane; cometabolic aerobic; pilot test
Hill AFB, Site 280	UT	Not Specified	FS Ongoing	BTEX, PHC	1990	1.03	271,000 (1)	NR	NC	Interim costs
Hill AFB, Site 914	UT	Other	FS Complete	BTEX, PHC	1989	1.03	863,000 (1)	5,000	173	Early bioventing application; combined with SVE
Lowry AFB (*in situ*)	CO	Other	FS Complete	BTEX, PHC	1992	1.03	75,300 (1)	NR	NC	Interim costs; high initial contaminant concentrations; used horizontal trenches
***In Situ* Bioremediation (Groundwater)**										
Avco Lycoming Superfund Site	PA	Superfund	FS Ongoing	cVOCs, Heavy metals	1997	1.03	455,000 (1)	NR	NC	Direct injection of molasses; anaerobic; air sparging, with SVE
Edwards AFB	CA	Superfund	DS Complete	cVOCs	1995	1.15	445,000 (1)	1,517	293	Recirculation between two aquifer systems; aerobic

Exhibit 2-4. Summary of Bioremediation Projects with Fully-Defined Cost Data
(Page 3 of 3)

Site Name	State	Cleanup Under	Status	Contaminants	Start Year	Area Cost Factor	Technology Cost ($)* (Source)	Volume Treated (yd^3)	Unit Cost ($\$/yd^3$)	Comments
Pinellas Northeast Site, Anaerobic Bioremediation	FL	RCRA CA	DS Complete	cVOCs	1997	0.87	359,000 (1)	1,238	290	Recirculation with addition of benzoate, lactate, and methanol; anaerobic; intended to supplement active pump-and-treat system
Texas Gulf Coast Site	TX	Other	FS Complete	cVOCs	1995	0.82	630,000 (1)	NR	NC	Recirculation with addition of methanol; anaerobic; intended as a precursor to monitored natural attenuation
Department of Energy, Savannah River Site, M Area Process Sewer/Integrated Demonstration Site	SC	Superfund	DS Complete	cVOCs	1992	0.87	729,000 (1)	NR	NC	Direct injection of cometabolites; aerobic; SVE employing horizontal wells

Sources: (1) FRTR case studies (volumes 1 [1995], 5 [1997], and 7 [1998] and CD-ROM [2000]). Available at *http://www.frtr.gov/cost*.
(2) *Cost Data for Innovative Treatment Technologies*, USACE, Internal Draft, July 1997.

Notes:

* Costs are the sum of capital and annual O&M costs for the technology and have been adjusted to a common location and year 1999, as discussed in Section 1.
** *Ex situ* soil projects are land treatment, unless otherwise noted.

AFB = Air Force Base
BTEX = Benzene, toluene, ethylbenzene, and xylenes
CA = Corrective Action
cVOC = Chlorinated volatile organic compound
DS = Demonstration scale
FS = Full-scale
NC = Not calculated
NR = Not reported
Other VOC = Other volatile organic compound (for example, ketones)
OU = Operable Unit
PAH = Polycyclic aromatic hydrocarbon
PCB = Polychlorinated biphenyl
PHC = Petroleum hydrocarbons
RCRA = Resource Conservation and Recovery Act
UST = Underground Storage Tank
SVE = Soil Vapor Extraction
SVOC = Semivolatile organic compound
yd^3 = Cubic yard

concentrations of nutrients, and concentration of electron acceptors affect the types of degradation mechanisms that are likely to occur and the rate of degradation. For *ex situ* bioremediation, parameters such as moisture content and pH may require adjustment before treatment, depending on the bioremediation mechanism and types of additives used. The moisture content of the soil also may affect the need for leachate collection and treatment.

Hydrogeologic setting: The permeability, heterogeneity, depth to groundwater, and thickness of the aquifer, along with the site type and aquifer chemistry, affect the complexity of the system in terms of the type of engineered solutions required and the extent to which such solutions are needed. A site that has low permeability and is highly stratified may require the use of pneumatic fracturing to improve conditions for use of bioremediation.

Amendments: The cost of amendments is affected by the price of the specific amendment used (including mixtures and proprietary solutions), the total amount required during operation, the complexity of the delivery mechanism, and the effectiveness of the amendment in treating the target contaminant(s).

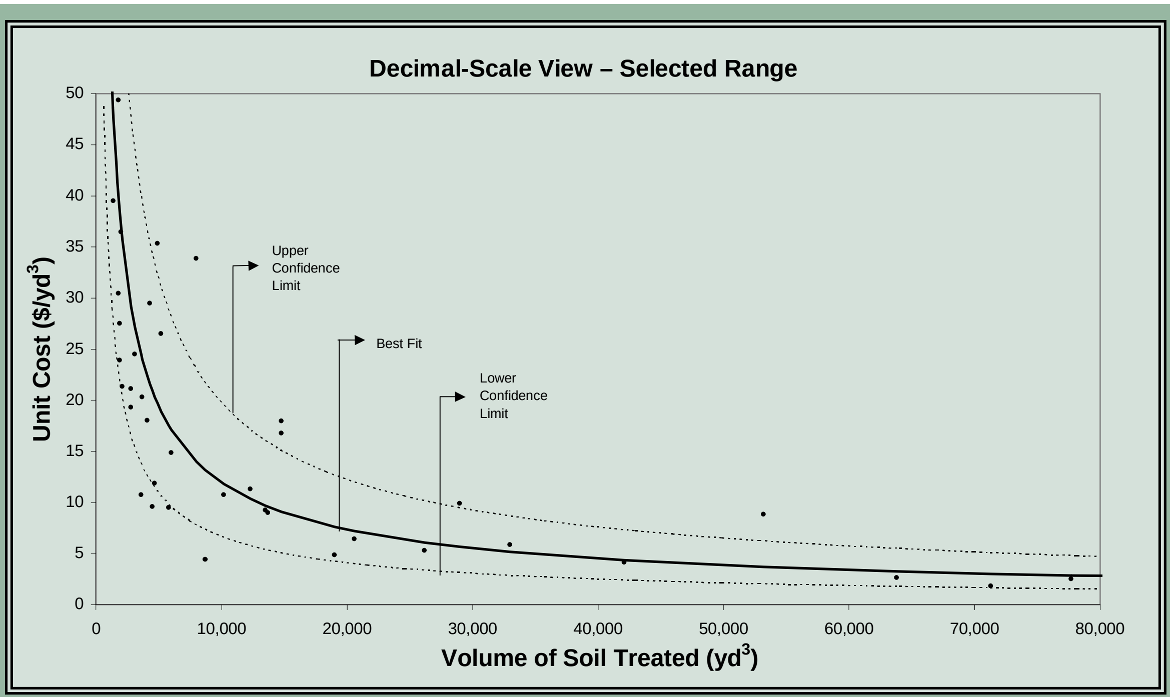
Type and extent of contamination: The type, concentration, and areal extent of contamination affect the size of the system (number of injection and extraction wells and blower size); the need for and complexity of off-gas treatment; the length of time the system must be operated to reach cleanup targets; the type and amount of amendments needed; the specific degradation mechanisms that may occur; and the rate and effectiveness of those mechanisms in treating the targeted contaminants. For *in situ* bioremediation, the presence of non-aqueous phase liquids (NAPLs) may require source control, with the type and extent of the NAPL contamination determining the complexity and potential effectiveness of the source control. For *ex situ* bioremediation, the type and concentration of contaminants determine the need for and type of liner, leachate collection, and emissions controls.

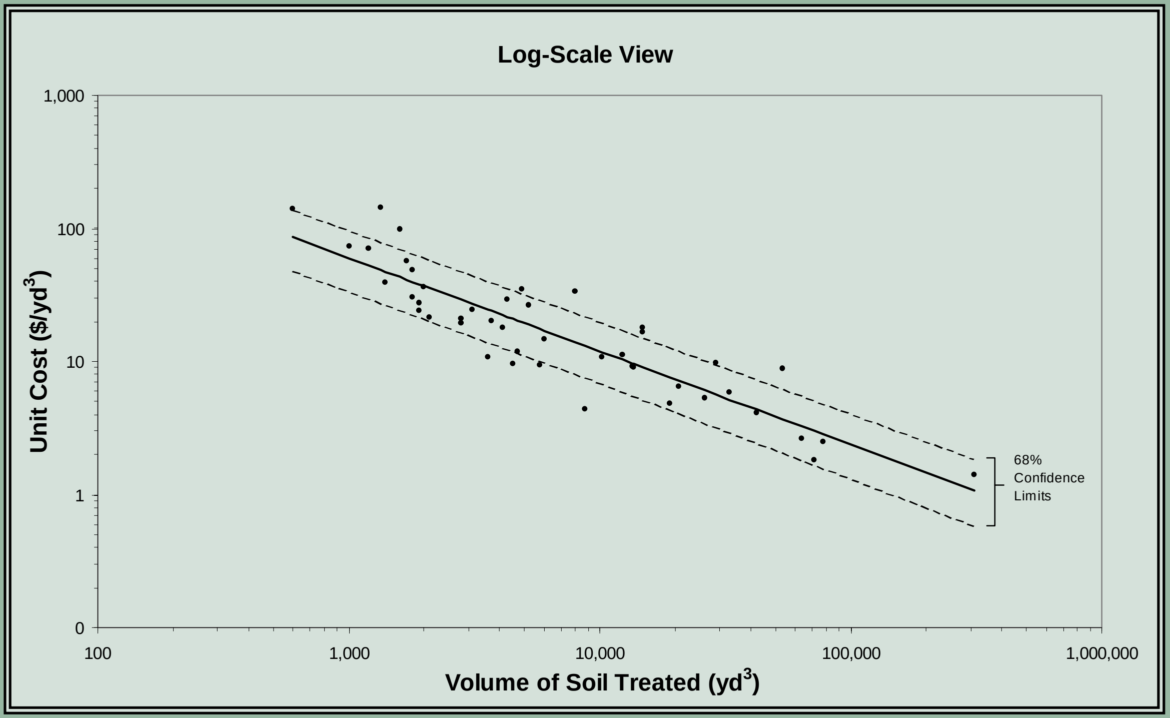
Results of Analysis of AFCEE Data - Unit Cost Versus Quantity Treated

The data for the individual AFCEE bioventing applications were adjusted on the basis of site location, as described in Section 1. However, because no information about the period of operation was available, costs could not be adjusted for inflation. The cost data then were evaluated to determine whether any correlations in unit cost versus quantity of soil treated were evident. A reverse-exponential linear fit was calculated for the data, as described in Section 1. Exhibit 2-5 presents the results of the analysis on both decimal-scale and logarithmic-scale plots. Appendix B provides the detailed backup for the analyses, including alternate confidence interval calculations. Exhibit 2-6 summarizes the information provided for the 45 AFCEE bioventing sites.

As Exhibit 2-5 shows, a correlation between unit costs and volume of soil treated is evident for the AFCEE bioventing projects. Economies of scale were observed where unit costs decreased as larger quantities were treated. For example, unit costs for projects decrease from about \$10 to \$20 per cubic yard for 10,000 cubic yards of soil treated to less than \$5 per cubic yard for projects where relatively large quantities of soil were treated.

Exhibit 2-5. AFCEE Bioventing Projects – Unit Cost vs. Volume Treated (with 68-Percent Confidence Interval)





Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 45 bioventing projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which less than 80,000 cubic yards of soil were treated and the unit cost was less than $50 per cubic yard.)

[2] All reported costs were adjusted for site locations, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 80 percent.

[4] Appendix B presents the methodology and other statistical information related to the plots above.

Exhibit 2-6. AFCEE Bioventing Projects

Site Name	Site Location	Treatment Volume (yd^3)	Total Cost ($)	Unit Cost ($/yd^3)
AFP 4	TX	1,800	599,000	333
AFP PJKS	CO	2,100	47,600	22.7
Battle Creek ANGB	MI	8,700	53,600	6.16
Beale AFB	CA	42,100	232,000	5.51
Bolling AFB	DC	10,200	99,000	9.71
Camp Pendeleton	CA	4,100	97,900	23.9
Cannon AFB	NM	13,500	128,000	9.48
Cape Canaveral AFB	FL	4,900	131,000	26.7
Charleston AFB	SC	1,600	120,000	75.0
Davis-Monthan	AZ	311,500	423,000	1.36
Dyess AFB	TX	2,000	49,000	24.5
Edwards AFB	CA	4,300	168,000	39.1
Eglin AFB	FL	12,300	105,000	8.54
Ellsworth AFB	SD	3,700	68,000	18.4
Elmendorf AFB	AK	19,000	237,000	12.5
Fairchild AFB	WA	8,000	310,000	38.8
FE Warren AFB	WY	2,800	53,000	18.9
Ft. Drum	NY	1,900	68,800	36.2
Grissom AFB	IN	6,000	87,400	14.6
Hanscom AFB	MA	3,600	48,500	13.5
Hickam AFB	HI	13,700	270,000	19.7
Hill AFB	UT	77,700	207,000	2.70
K.I. Sawyer AFB	MI	71,300	179,000	2.50
Kelly AFB	TX	33,000	130,000	3.94
Kirtland AFB	NM	3,100	77,500	25.0
LA AFB	CA	20,600	176,000	8.54
Little Rock AFB	AR	1,000	55,500	55.5
Malmstrom AFB	MT	1,400	71,900	51.4
March AFB	CA	1,200	113,000	94.2
McClellan AFB	CA	53,200	622,000	11.7
McGuire AFB	NJ	2,800	82,400	29.4
Mt. Hope AFB	ID	1,900	58,700	30.9
Nellis AFB	NV	26,200	181,000	6.91
Offutt AFB	NE	14,800	219,000	14.8
Patrick AFB	FL	1,350	146,000	108
Pease AFB	NH	14,800	293,000	19.8
Plattsburgh AFB	NY	63,800	255,000	4.00
Pope AFB	NC	1,700	69,600	40.9
Randolph AFB	TX	4,700	37,500	7.98
Shaw AFB	SC	5,200	104,000	20.0
Tinker AFB	OK	1,800	41,500	23.1
Travis AFB	CA	600	112,000	187
USCG Supp. Cen. Kodiak	AK	4,500	110,000	24.4
Vandenberg AFB	CA	29,000	380,000	13.1
Westover AFB	MA	5,800	69,200	11.9

Source: *Bioventing Performance and Cost Results from Multiple Air Force Test Sites, Technology Demonstration, Final Technical Memorandum.* AFCEE Technology Transfer Division. June 1996.

3.0 THERMAL DESORPTION

Thermal desorption is used to treat contaminated soil by heating the soil (directly or indirectly) to a target temperature to cause the organic contaminants to volatilize and separate from the soil. The volatilized contaminants (vapors) are collected and generally are treated by one or more off-gas treatment technologies. Types of off-gas treatment include filtration, wet-scrubbing, vapor-phase carbon adsorption, and thermal oxidation. This section presents a summary of data obtained from case studies of on-site, *ex situ* thermal desorption and the results of the analysis of those data.

Methodology for Cost Analysis for Thermal Desorption Projects

As Exhibit 3-1 shows, 35 thermal desorption case studies involving 29 individual projects[4] were identified from the available information sources.

Exhibit 3-1. Thermal Desorption Case Studies - Sources

Source	Number of Case Studies
FRTR thermal desorption case studies (Volumes 1 [1995], 5 [1997], and 7 [1998] and CD-ROM [2000]). Available at *http://www.frtr.gov/cost*.	18
A Compendium of Cost Data for Environmental Remediation Technologies, LANL, LA-UR-96-2205, August 1996. Available at *htttp://www.lanl.gov/orgs/d/d4/enviro/etcap*.	10
Case studies presented in *Cost Data for Innovative Treatment Technologies*, USACE, July 1997.	7

Capital and O&M costs were obtained from the case studies, along with data needed to calculate unit costs, such as volume of material treated. Of the 29 thermal desorption projects identified, it was determined that fully defined cost data, as described in Section 1, were available for 22. For *ex situ* projects with fully-defined cost data, costs for excavation and disposal of residues were not included in the calculation of unit cost. Exhibit 3-2 presents summary information about the 21 projects, including name, location, contaminants, cost information, and information about the technology.

Results

Unit Cost Versus Quantity of Soil Treated

The costs of thermal desorption projects were evaluated to determine whether any correlations in unit cost versus quantity of soil treated were evident. Initially, the analysis was performed using all 21 projects with fully-defined cost data. Preliminary results showed that several projects appeared to have much higher relative unit costs. Additional analysis indicated that projects where PCBs were present in the contaminated soil generally exhibited higher unit costs than projects where PCBs were not present. Further review indicated that the types of emissions controls used for projects where PCBs were present differed substantially different from those used for projects where PCBs were not present. For example, most of the projects where PCB-contaminated soil was treated required the use of complex emissions control systems, such as a liquid-phase oxidation system. Therefore, it was determined that projects involving PCB-contaminated soil did not involve technologies having characteristics similar to those projects that did not involve PCBs, and that the two types of projects should be analyzed separately.

For the 17 projects under which PCBs were not a contaminant, a reverse-exponential linear fit was calculated for the data, as described in Section 1. Exhibit 3-3 presents the results of the analysis on both decimal-scale and logarithmic-scale pilot. Appendix B presents the detailed backup for the analyses, including alternate confidence internal calculations. As Exhibit 3-3 shows, a correlation between unit costs and volume of soil treated is evident. Economies of scale were observed where unit costs decreased as larger quantities were treated. For example, unit costs for projects where 20,000 tons of soil were treated were

Exhibit 3-2. Summary of Thermal Desorption Projects with Fully Defined Cost Data (Page 1 of 2)

Site	Application Data							Contaminants							Emission Controls				
	Application Year	**Location**	**Cost * ($) (with source)**	**Tons Treated**	**$/Ton**	**% Soil Moisture**	**Treatment Temperature (degrees F)**	PHC	Metal	VOC	CVOC	SVOC	PCB	Rad	VGAC	VScrubber	VThermal	LGAC	LOx
Waldick Aerospace Devices Superfund Site	1993	NJ	2,890,000 (1)	5,175	558	13	500	X	X	X						X	X		
Re-Solve, Inc. Superfund Site	1994	MA	24,100,000 (1)	44,000	548	8.9	750	X				X	X		X	X		X	X
Port Moller Radio Relay Station	1995	AK	7,070,000 (1)	14,250	496	11	1200	X		X							X		
Wide Beach Development Superfund Site	1990	NY	19,300,000 (1)	42,000	459	18.3	1293					X	X		X	X		X	X
Outboard Marine Corporation Superfund Site	1992	IL	4,720,000 (1)	12,755	370	12.9	1339					X	X		X	X		X	X
Reich Farm Superfund Site	1995	NJ	6,010,000 (1)	22,245	270	NA	NA			X	X	X					X		
Rocky Flats Environmental Technology Site	1996	CO	1,480,000 (1)	5,694	260	NA	250		X	X	X			X	X				
McKin Company Superfund Site	1986	ME	4,340,000 (1)	17,250	252	NA	400			X	X	X				X		X	
Sarney Farm Superfund Site	1997	NY	2,900,000 (1)	10,571	234	<25	700			X	X								
Sand Creek Industrial Superfund Site, OU 5	1995	CO	2,280,000 (1)	13,000	175	NA	500		X			X			X	X		X	
Naval Air Station Cecil Field	1995	FL	1,960,000 (1)	11,768	167	12.9	825			X	X	X					X		
Letterkenny Army Depot	1994	PA	3,410,000 (2)	20,979	162	24	600		X	X	X	X	X		X				
Metaltec	1995	NJ	1,206,000 (1)	6,104	197	NA	750				X					X	X		
Arlington Blending & Packaging Superfund Site	1996	TN	4,090,000 (1)	41,431	98.7	17	680		X			X			X	X			
TH Agriculture & Nutrition Company Superfund Site	1993	GA	371,000 (1)	4,300	86.3	16	1080					X			X	X		X	
FCX Washington Superfund Site	1995	NC	1,610,000 (1)	20,386	79.0	15	350					X			X				

Exhibit 3-2. Summary of Thermal Desorption Projects with Fully-Defined Cost Data
(Page 2 of 2)

	Application Data							**Contaminants**							**Emission Controls**				
Site	**Application Year**	**Location**	**Cost * ($) (with source)**	**Tons Treated**	**$/Ton**	**% Soil Moisture**	**Treatment Temperature (degrees F)**	PHC	Metal	VOC	CVOC	SVOC	PCB	Rad	VGAC	VScrubber	VThermal	LGAC	LOx
Longhorn Army Ammunition Plant, Burning Ground No. 3	1997	TX	3,910,000 (1)	51,669	75.7	17.5	430			X	X					X	X		
Alameda Naval Air Station, Interim Soil Removal	1993	CA	154,000 (3)	2,250	68.4	NA	NA	X											
Fort Lewis Solvent Refined Coal Pilot Plant	1996	WA	4,110,000 (1)	104,336	39.4	4	750	X	X			X					X		
Fort Campell POL Site	1994	KY	1,230,000 (3)	32,404	38.0	NA	NA	X											
Dane County Regional Airport, Truaz Field	1994	WI	1,150,000 (3)	34,862	33.0	NA	NA	X		X							X		

Sources:

(1) FRTR case studies (volumes 1 [1995], 5 [1997], and 7 [1998] and CD-ROM [2000]). Available at <*http://www.frtr.gov/cost*>.
(2) *A Compendium of Cost Data for Environmental Remediation Technologies*. LANL. LA-UR-96-2205. August 1996. Available at <*http://www.lanl.gov/orgs/d/d4/enviro/etcap*>.
(3) *Cost Data for Innovative Treatment Technologies*, internal USACE draft. July 1997.

Notes :

[*] Cost are the sum of capital and annual O&M costs for the technology and have been adjusted to a common location and year 1999 as discussed in Section 1. Where excavation and disposal of residuals were specifically identified as a separate cost elements, they were excluded from the technology cost and unit cost calculation.

BTEX = Benzene, toluene, ethylbenzene, and xylene
cVOCs = Chlorinated volatile organic compound
DS = Demonstration scale
LGAC = Granular activated carbon treatment for liquid phase
LOx = Oxidative treatment for liquid phase
NA = Not available
NC = Not calculated
NR = Not reported
OU = Operable unit
Other VOCs = Other volatile organic compound (for example, ketones)

PAHs = Polycyclic aromatic hydrocarbon
PCBs = Polychlorinated biphenyl
PHC = Petroleum hydrocarbon
POL = Petroleum, oil and lubricant
Rad = Radionuclides
SVOCs = Other semivolatile organic compound
VGAC = Granular activated carbon treatment for gas phase
Vscrubber = Wet scrubber treatment for gas phase
Vthermal = Thermal treatment for gas phase
yd^3 = Cubic yards

approximately $100 to $300 per ton; costs decreased to less than $50 per ton for projects treating relatively larger quantities of soil.

Because PCBs were treated at fewer than five projects, a quantitative analysis of unit cost versus quantity of soil treated was not performed. However, qualitative information from the case studies indicates that potential factors contributing to the relatively higher cost of treatment for projects where PCBs are a contaminant include types of emissions control technologies required (discussed above), the need to operate the thermal desorption unit at higher temperatures, and the type of liquid effluent controls required.

Other Factors

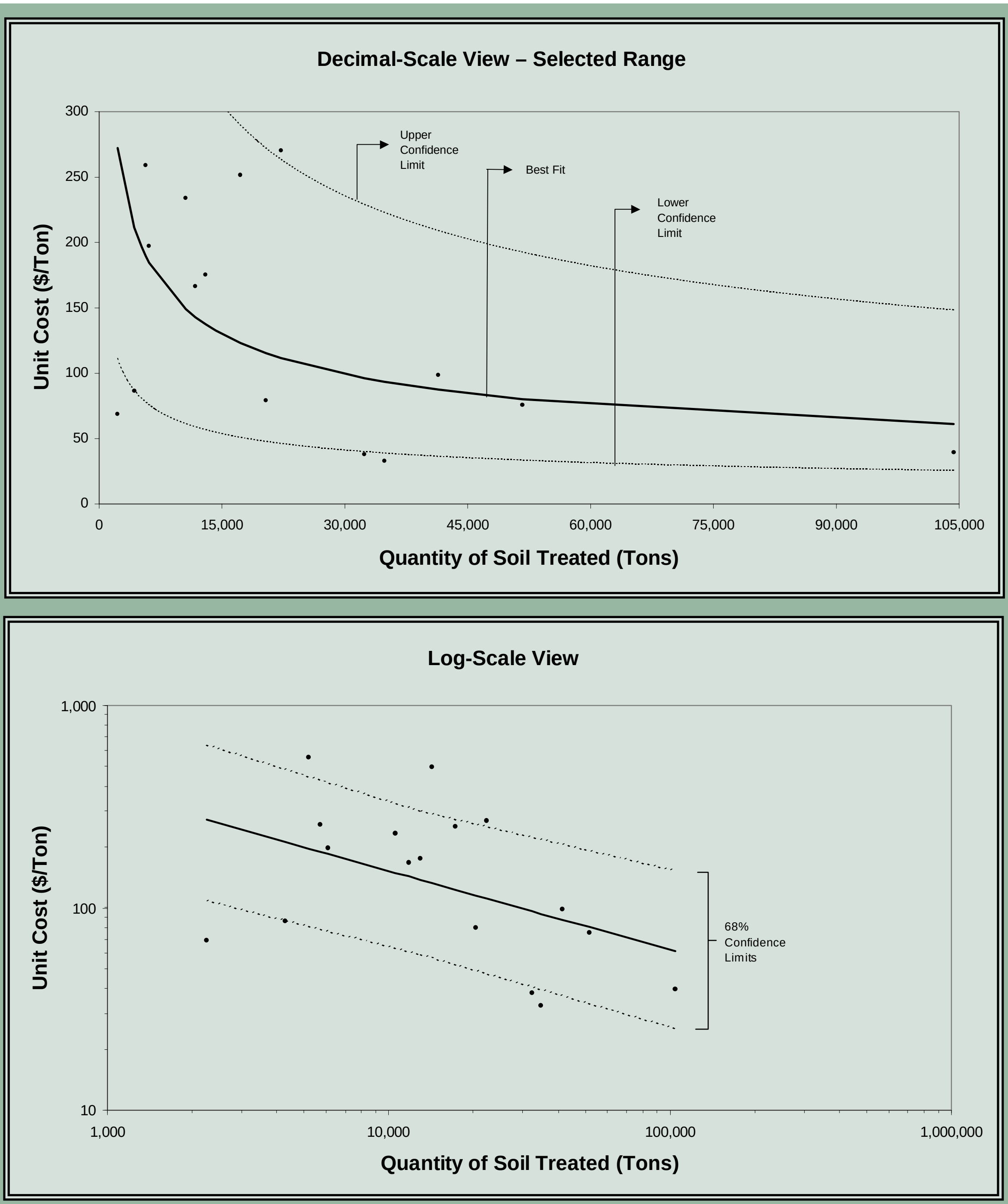
Potential correlations between unit cost and other factors, such as throughput, moisture content, and treatment temperature, were considered, but no correlations were evident. While quantitative correlations for those factors were not evident, the following qualitative information about potential factors affecting the design and operation of *ex situ* thermal desorption systems was provided in the case studies. The specific effects of those and other factors on the cost of a thermal desorption system are site-specific.

Soil type and matrix characteristics: Clay content, particle size, moisture content, and pH determine the need for pretreatment of soil before thermal desorption to avoid such operational problems as slagging and clogging of the feed mechanism. Pretreatment may include screening to adjust particle size, chemical treatment to adjust pH, and dewatering to adjust moisture content.

Type and concentration of contaminants: The type and concentration of contaminants affect the operating temperature, the need to operate under a vacuum or with a reducing or inert atmosphere, and the type of off-gas treatment needed. For example, thermal desorption of soils that contain high concentrations of chlorinated compounds generally uses higher temperatures, is performed under a vacuum, and uses more complex off-gas treatment (an acid-gas scrubber or thermal oxidizer) than thermal desorption of soils that contain non-chlorinated compounds. However, a comparison of thermal desorption projects that had chlorinated compounds versus those without chlorinated compounds did not show a substantial difference in unit costs and the cost curve shown above includes both types of projects.

Maintenance: The type and amount of maintenance needed for the thermal desorption system can affect the project schedule and costs. For the feed mechanism and thermal desorption unit, adequate characterization of the soil type and matrix characteristics are important to minimizing downtime, as described above. For off-gas treatment, the properties of the off-gas, including contaminant concentrations and levels of particulates, affect the length of time a treatment technology operates before routine maintenance is needed (for example, changeout of carbon or filters) and the frequency with which non-routine maintenance is needed (for example, clogging of a baghouse). Depending on the type and extent of the maintenance needs, the design and operation of the thermal desorption system may be modified.

Exhibit 3-3. Thermal Desorption Projects – Unit Cost vs. Quantity of Soil Treated (with 68-Percent Confidence Interval)



Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 17 thermal desorption projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which less than 105,000 tons of soil were treated and the unit cost was less than $300 per ton.)

[2] All reported costs were adjusted for location and time, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 21 percent.

[4] Appendix B presents the methodology and other statistical information related to above plots.

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4.0 SOIL VAPOR EXTRACTION

Soil vapor extraction (SVE) is an *in situ* remedial technology that is used to remove volatile organic contaminants from soil. Air is drawn through the subsurface by applying a vacuum to one or more extraction points, from which the vapor phase of the volatile contaminants is removed. The soil vapors (off-gases) from the system are collected and generally treated by one or more technologies, such as granular activated carbon (GAC), thermal oxidation, catalytic oxidation, or scrubbing. SVE often is used with other technologies such, as air sparging, to enhance the removal of biodegradable contaminants or to strip volatile contaminants from the saturated zone, respectively. This section presents a summary of data obtained from case studies of SVE applications and an analysis of those data.

Methodology for Cost Analysis for SVE Projects

Exhibit 4-1 shows 44 SVE case studies addressing 35 individual projects[5] that were identified from the available information sources.

Exhibit 4-1. SVE Projects - Sources

Source	Number of Case Studies
FRTR SVE case studies (for example, volumes 1 [1995], 5 [1997], 7 [1998] and CD-ROM [2000]). Available at *http://www.frtr.gov/cost*.	28
A Compendium of Cost Data for Environmental Remediation Technologies, LANL, LA-UR-96-2205, August 1996. Available at *http://www.lanl.gov/orgs/d/d4/enviro/etcap*.	11
Case studies presented in *Cost Data for Innovative Treatment Technologies*, USACE, July 1997.	5

Capital and O&M costs were obtained from the case studies, along with data needed to calculate unit costs, such as the quantity of soil treated or mass of contaminant removed. Of the 35 SVE projects identified, it was determined that fully defined cost data, as described in Section 1, were available for 23. Exhibit 4-2 presents information about each of these projects, including site name, location, contaminants, and cost data. For each of the three ongoing projects, the total cost reflects the information reported in the case study for a specified period of operation and may not be the final cost of the project.

The case studies provided information about quantity treated in terms of (1) volume of soil treated and/or (2) mass of contaminant removed. Therefore, unit costs were calculated both ways, according to the information available in the case study. Volume of soil treated was standardized to cubic yards on the basis of soil density (assumed to be 1.5 tons per cubic yard when not specified). For the 23 projects for which fully defined costs were available, unit cost was calculated on the basis of quantity of soil treated for18 sites and on the basis of mass of contaminant removed for 14 sites.

Results

The costs of SVE projects were evaluated to determine whether any correlations in unit cost versus quantity of soil treated or mass of contaminant removed were evident. A reverse-exponential linear fit was calculated for the data, as described in Section 1. The results of the analysis are presented on both decimal-scale and logarithmic-scale plots. Appendix B presents the detailed backup for the analyses, including alternate confidence interval calculations.

Unit Cost Versus Volume of Soil Treated

Exhibit 4-3 presents the results of the analysis of unit cost versus volume of soil treated for 18 projects. A correlation between unit cost and volume of soil treated is evident for the SVE projects. Economies of scale were observed where unit costs decreased as larger quantities were treated. For example, units costs decreased from $60 to $350 per cubic yard for projects treating up to 10,000 cubic yards of soil to less than $5 per cubic yard for projects treating relatively larger quantities of soil.

Exhibit 4-2. Summary of SVE Projects with Fully-Defined Cost Data (Page 1 of 2)

Site Name	Location	Project Status	Contaminants	Off-gas Treatment	Total Cost ($)*	Volume Treated (yd^3)	Mass of Contaminant Removed (pounds)**	Cost/yd^3 Treated	Cost/Pound Contaminant Removed
Amcor Precast	UT	Ongoing	PHC, BTEX	NA	240,610	7,500	NA	32.08	NC
Camp LeJeune Military Reservation Superfund Site, Site 82, Area A	NC	Completed	cVOCs, BTEX	GAC	591,305	17,500	NA	35.79	NC
Commencement Bay, South Tacoma Channel Well 12A Superfund Site	WA	Completed	cVOCs	NA	4,477,689	41,720	NA	107.33	NC
Davis-Monthan AFB, Site ST-35	AZ	Completed	cVOCs	thermal oxidizer	225,909	63,000	585,700	3.59	0.39
Defense Supply Center Richmond Superfund Site	VA	Completed	cVOCs	GAC	97,745	1,000	NA	102.64	NC
Fairchild Semiconductor Corporation Superfund Site	CA	Completed	cVOCs, BTEX	GAC	4,442,609	42,000	16,000	105.78	277.66
Fort Lewis Landfill 4	WA	Ongoing	cVOCs, Metals	GAC	1,623,250		60	NC	27,054.16
Garden State Cleaners	NJ	Completed	cVOCs	GAC	197,009	600	NA	328.35	NC
Hastings Groundwater Contamination Superfund Site, Well Number 3 Subsite	NE	Completed	cVOCs	GAC	456,862	185,000	600	2.47	761.44
Holloman AFB, Sites 2 and 5	NM	Ongoing	BTEX	Bioreactor	646,632	9,500	44,000	68.07	14.7
Intersil/Siemens Superfund Site	CA	Completed	cVOCs	GAC	801,299	280,000	3,000	2.86	267.10
Kelly AFB, Area 1100	TX	Completed	PHC	NA	737,446	8,900	NA	82.86	NC
Luke Air Force Base, North Fire Training Area	AZ	Completed	BTEX, VOCs	thermal oxidizer	601,296	NA	12,000	NC	50.11
Rocky Mountain Arsenal Superfund Site, Motor Pool Area, OU 18	CO	Completed	cVOCs	GAC	212,399	34,000	70	6.25	3,034.27
Sacramento Army Depot Superfund Site, Burn Pits OU	CA	Completed	VOCs, cVOCs	GAC	677,417	650	2,300	1,042.18	294.53
Sacramento Army Depot Superfund Site, Tank 2, OU 3	CA	Completed	cVOCs	GAC	517,089	247,900	138	2.09	3,747.02
Sand Creek Industrial Superfund Site, OU 1	CO	Completed	cVOCs, PHC	catalytic oxidation	2,284,944	31,440	176,500	72.68	12.95
Shaw AFB, OU 1	SC	Ongoing	PHC	catalytic oxidation	2,776,862	83,333	518,250	33.32	5.36

Exhibit 4-2. Summary of SVE Projects with Fully-Defined Cost Data (Page 2 of 2)

Site Name	Location	Project Status	Contaminants	Off-gas Treatment	Total Cost ($)*	Volume Treated (yd^3)	Mass of Contaminant Removed (pounds)**	Cost/yd^3 Treated	Cost/Pound Contaminant Removed
SMS Instruments Superfund Site	NY	Completed	cVOCs, VOCs, PHC	catalytic oxidation, scrubbing	413,171	1,250	NA	330.54	NC
Twin Cities Army Ammunition Plant	MN	Completed	cVOCs	GAC	844,889	NA	551,465	NC	1.53
UST, Big Rapids	MI	Completed	VOCs, PHCs	GAC	244,070	NA	45,000	NC	5.42
Verona Well Field Superfund Site, Thomas Solvent Raymond Road OU 1	MI	Completed	cVOCs	GAC, catalytic oxidation	1,753,833	27,600	NA	63.54	NC

Sources:

(1) FRTR case studies (volumes 1 [1995], 5 [1997], and 7 [1998] and CD-ROM [2000]). Available at *<http://www.frtr.gov/cost>*.

(2) *A Compendium of Cost Data for Environmental Remediation Technologies.* LANL. LA-UR-96-2205. August 1996. Available at *<http://www.lanl.gov/orgs/d/d4/enviro/etcap>*.

(3) *Cost Data for Innovative Treatment Technologies*, Internal USACE draft. July 1997.

Notes:

* Cost are the sum of capital and annual O&M costs for technology and have been adjusted to a common location and year 1999 as discussed in Section 1.
** Mass of contaminants removed was reported in the case studies as total volatile organic compounds or as the sum of individual contaminants.

BTEX = Benzene, toluene, ethylbenzene, and xylene
cVOCs = Chlorinated volatile organic compound
DS = Demonstration scale
GAC = Granular activated carbon
NA = Information not available
NC = Not calculated
NR = Not reported
Other VOCs = Other volatile organic compound (for example, ketones)
PAHs = Polycyclic aromatic hydrocarbon
PCBs = Polychlorinated biphenyl
PHC = Petroleum hydrocarbon
SVOCs = Semivolatile organic compound

Unit Cost Versus Mass of Contaminant Removed

Exhibit 4-4 presents the results of the analysis of unit cost versus mass of contaminant removed for 14 projects. A correlation between unit cost and mass of contaminant removed is evident for the SVE projects. Economies of scale were observed where unit costs decreased as larger quantities were treated. For example, units costs for projects decreased from $300 to 900 per pound for projects where up to 3,000 pounds of contaminant were removed to less than $15 per pound for projects where relatively larger quantities of contaminant were removed. Units costs were less than $2 per pound for projects where more than about 500,000 pounds of contaminant were removed.

Other Factors

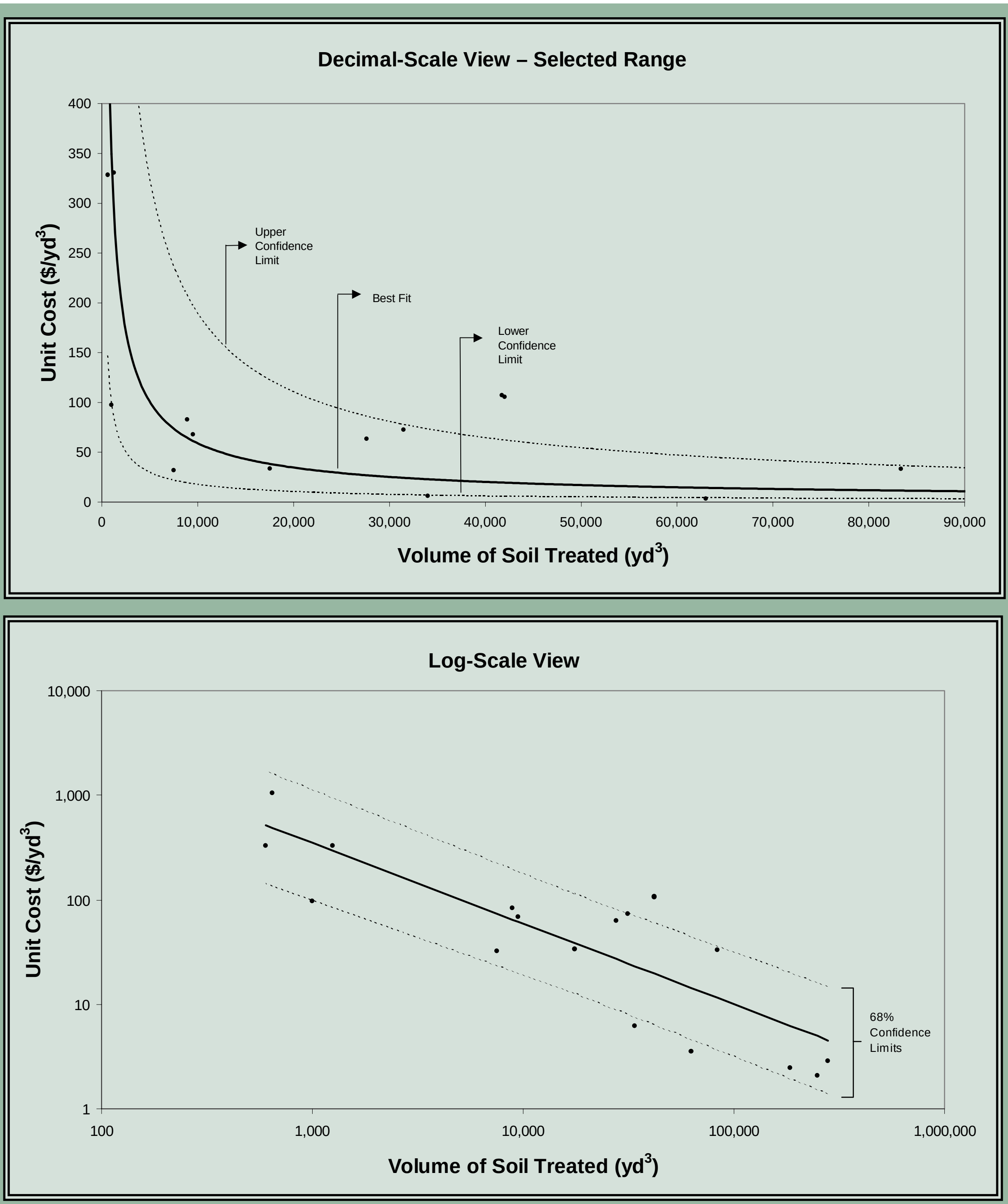
Potential correlations between unit cost and other factors, such as throughput, moisture content, type of contaminant, and type of off-gas treatment, were considered, but no correlations were evident. While quantitative correlations for those factors were not evident, the following qualitative information about potential factors affecting the design and operation of SVE systems was provided in the case studies and in the EPA report *Analysis of Selected Enhancements for Soil Vapor Extraction,* September 1997. The specific effects of those and other factors on the cost of SVE systems are site-specific.

Soil type and hydrogeologic setting: The permeability, porosity, moisture content, and heterogeneity of the soil; the depth and stratigraphy of the contamination in the subsurface; and the extent of seasonal variations in the water table affect the number and placement of the extraction wells, the radius of influence of the extraction wells, the ease with which contamination can be removed from the subsurface, and the length of time needed to reach cleanup targets. For SVE, it was generally true that the more permeable the soil, the easier it is to extract the contaminants.

Properties of the contaminant and extent of contamination: The properties and concentration of contaminants, along with the areal extent of contamination, affect the size of the system (number of extraction wells and blower size); the need for and complexity of off-gas treatment; and the length of time the system must be operated to reach cleanup targets. For example, SVE generally is more effective for contaminants that have vapor pressures greater than 1 millimeter of mercury (mm Hg) at 20°C. The presence of chlorinated compounds may require the use of more complex off-gas treatment, such as thermal oxidation, while carbon adsorption can be used for non-chlorinated compounds. In addition, the presence of NAPLs may require source control, with the type and extent of the NAPL contamination determining the complexity and potential effectiveness of the source control.

Enhancements: Enhancement technologies, such as hot-air injection, horizontal wells, air sparging, and pneumatic and hydraulic fracturing, may be used when the contaminants or soil characteristics limit the effectiveness of SVE (for example, when conditions include low-permeability soil or when contaminants having low vapor pressures are present). Costs are affected by the type of enhancement used and by the effectiveness of the enhancement in improving performance of SVE.

Exhibit 4-3. Soil Vapor Extraction Projects – Unit Cost vs. Volume of Soil Treated (with 68 Percent-Confidence Interval)



Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 18 soil vapor extraction projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which less than 90,000 cubic yards of soil were treated or unit costs were less than $400 per cubic yard of soil treated).

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 69 percent.

[4] Appendix B presents the methodology and other statistical information related to the above plots.

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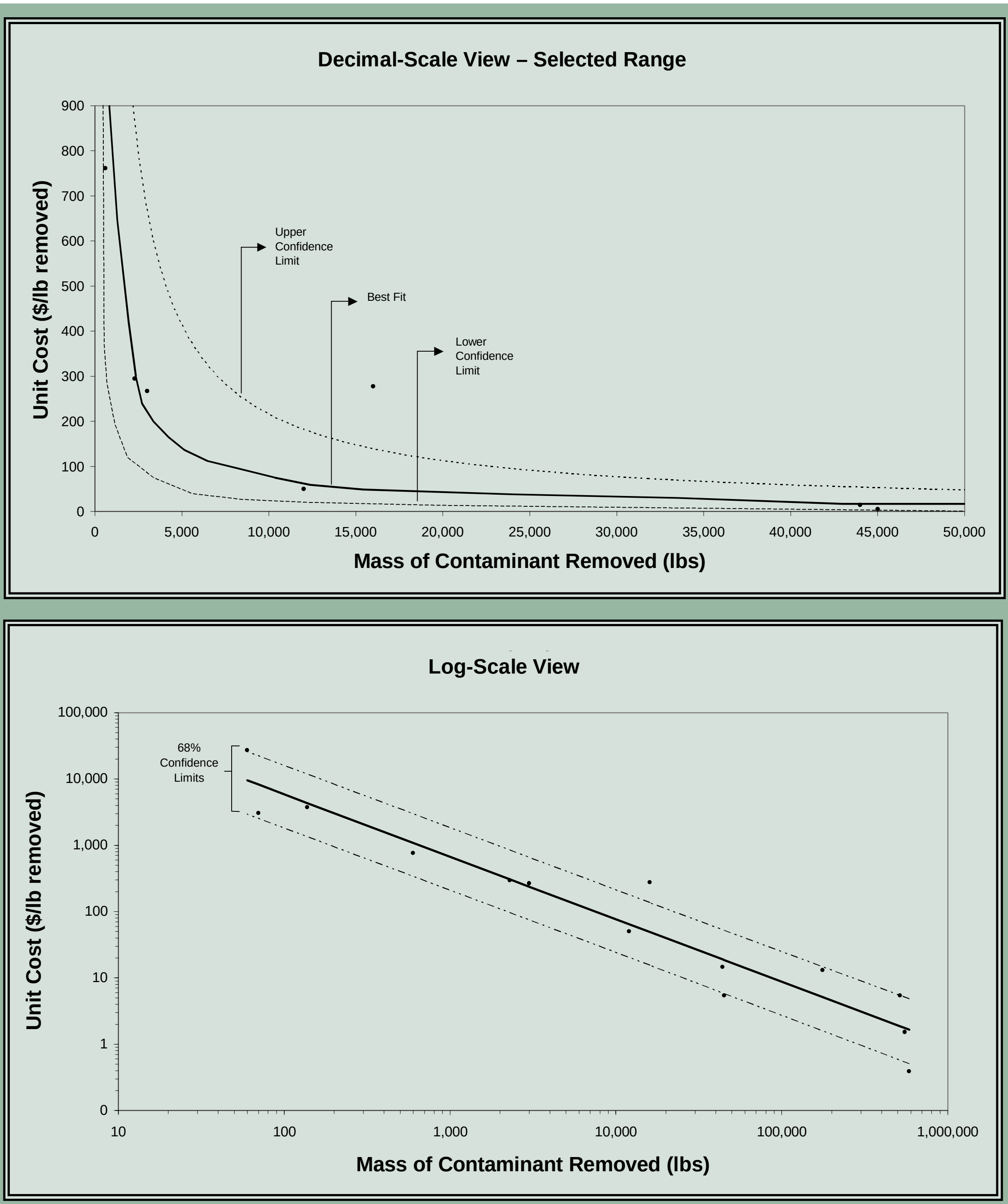
Exhibit 4-4. Soil Vapor Extraction Projects – Unit Cost vs. Mass of Contaminant Removed (with 68 Percent-Confidence Interval)



Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 14 soil vapor extraction projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which less than 50,000 pounds of contaminant was removed or unit costs were less than $900 per pound of contaminant removed).

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 92 percent.

[4] Appendix B presents the methodology and other statistical information related to the above plots.

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5.0 ON-SITE INCINERATION

Incineration uses controlled-flame combustion to volatilize and destroy organic contaminants. Common incinerator designs include the rotary kiln, which can be used to treat a variety of waste forms, such as solids, liquids, sludges, and debris, and liquid injection systems which are used to treat aqueous and non-aqueous wastes that can be atomized through a burner nozzle. An air pollution control system (APCS) is used to treat off-gases from the combustion process and generally includes one or more of the following components: cyclones, baghouses, gas-conditioning (quench) systems, scrubbers, and mist eliminators. This section presents a summary of data obtained from case studies of on-site incineration projects and the results of the analysis of those data.

Methodology for Cost Analysis for On-Site Incineration Projects

In total, 17 case studies addressing 17 individual projects where incineration was the primary technology used to remediate the contaminated media were identified from the available information sources. The case studies, prepared by the FRTR, were included in the report *FRTR Remediation Case Studies: On-Site Incineration, Volume 12* (1998) and CD-ROM (2000) and summarized in *On-site Incineration: Overview of Superfund Operating Experience*, March 1998.

Capital and O&M costs were obtained from the case studies, along with data needed to calculate unit costs, such as the quantity of soil treated. Of the 17 projects, fully defined cost data were identified for seven. Exhibit 5-1 presents summary information about those seven projects, including site name and location, contaminants, design, and cost data.

Results

Unit Cost Versus Quantity Treated

The costs of incineration projects were evaluated to determine whether any correlations in unit cost versus quantity of soil treated were evident. For the analysis, projects were grouped by similar characteristics on the basis of physical properties of the media treated. Five projects treated solid media (such as soil, sludge, sediment, and debris) and two projects treated only liquids and fumes.

For the five incineration projects where solid media were treated, no correlations in unit cost versus quantity of soil treated were evident. Because the total number of projects under which liquids or fumes only were treated was fewer than five, no quantitative analysis of unit cost versus quantity of soil treated was performed.

Other Factors

Potential correlations between unit cost and other factors, such as throughput, moisture content, and treatment temperature, were considered, but but no correlations were evident. While the available cost data did not show specific correlations for those factors, the following qualitative information about the potential factors affecting the cost of incineration was provided in the case studies and in the EPA report *On-Site Incineration: Overview of Superfund Operating Experience*, March 1998.

Soil type and matrix characteristics: Clay content, particle size, moisture content, and pH determine the need for pretreatment of soil before incineration to minimize such potential operational problems as slagging, overpressurization, and clogging of the feed mechanism. Pretreatment may include screening to adjust particle size, chemical treatment to adjust the pH, and dewatering to adjust moisture content.

Type and concentration of contaminants: The type and concentration of contaminants affect the temperature and residence time and the type of off-gas treatment. For example, incineration of waste that contains high concentrations of chlorinated compounds generally uses more complex off-gas treatment (an acid-gas scrubber in addition to a cyclone and baghouse) to treat products of incomplete combustion.

Maintenance: The type and amount of maintenance needed for the incinerator can affect the project schedule and costs. For the incinerator, adequate characterization of the soil type and matrix characteristics are important in minimizing downtime, as described above. For off-gas treatment, the properties of the off-gas, including concentrations of contaminant and levels of particulates, affect the frequency with which non-routine maintenance is needed (for example, unclogging of a baghouse).

Exhibit 5-1. Summary of On-Site Incineration Projects with Fully-Defined Cost Data (Page 1 of 2)

Site Name and Location	Principal Contaminants	Medium	Incineration System Design	Period of Operation	Cost of Treatment ($) (1)	Quantity Incinerated	Calculated Unit Cost for Treatment	Comments
Bayou Bonfouca, LA	PAHs	Sediment	Rotary kiln, SCC, quench system, gas conditioner, scrubber, and mist eliminator	1993 - 1995	74,000,000	250,000 tons (169,000 yds^3)	$300/ton	Costs for incineration were paid on the basis of dry weight of ash rather than the weight of feed material
Celanese Corporation Shelby Fiber Operations, NC	Ethylene glycol VOCs PAHs Phenol	Soil and sludge	Rotary kiln, SCC, quench duct, baghouse, and packed-bed scrubber system	1991	2,000,000	4,660 tons	$440/ton	Relatively small amount of waste treated
Former Nebraska Ordnance Plant, NE	Explosives and propellants	Soil and debris	Rotary kiln, SCC, water quench, and mist eliminator	1997	7,000,000	16,449 tons	$430/ton	Shutdown of the system during a period of inclement weather resulted in higher costs than had been expected
MOTCO, TX	Styrene tars VOCs	Soil Sludge Organic liquids Aqueous wastes	Rotary kiln, SCC; second incinerator with single liquid injection chamber; both had quench system, gas conditioner, wet scrubber, and mist eliminator	1990 - 1991	33,000,000	23,021 tons total Soil (4,699 tons) Sludge (283 tons) Organic liquids (7,568 tons) Aqueous wastes (10,471 tons)	$1,400/ton	Mechanical problems during operation were attributed to inaccurate waste characterization
Petro Processors, LA	Chlorinated hydrocarbons PAHs Oils	Organic liquids and fumes	Horizontal liquid injection incinerator, quench tank, wet scrubber, particulate scrubber, entrainment separator	1994 - 1997	4,800,000	213,376 gallons (as of June 1997)	$22/gallon	Project is ongoing; costs reported are those through June 1997

Exhibit 5-1. Summary of On-Site Incineration Projects with Fully-Defined Cost Data (Page 2 of 2)

Site Name and Location	Principal Contaminants	Medium	Incineration System Design	Period of Operation	Cost of Treatment ($) (1)	Quantity Incinerated	Calculated Unit Cost for Treatment	Comments
Rocky Mountain Arsenal, CO	Organochlorine and organophosphorus pesticides	Liquids	Submerged quench incinerator, quench chamber, spray dryer, scrubber, and packed-tower scrubber	1993 - 1995	69,000,000	10,900,000 gallons	$6/gallon	Innovative design was used to capture metal particulates
Sikes Disposal Pits, TX	Organic and phenolic compounds	Soil and debris	Rotary kiln, SCC, quench section, and two-stage scrubber	1992 - 1994	81,000,000	Soil and debris (496,000 tons)	$160/ton	Project completed 18 months ahead of schedule because of use of larger incinerator than had been planned

Source:

FRTR case studies (volume 12 [1998] and CD-ROM [2000]). Available at <*http://www.frtr.gov/cost*>.

Notes:

[*] Cost are the sum of capital and annual O&M costs for technology and have been adjusted to a common location and year 1999 as discussed in Section 1.

PAHs = Polycyclic Aromatic Hydrocarbons
VOCs = Volatile Organic Compounds
SCC = Secondary combustion chamber

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6.0 PUMP AND TREAT SYSTEMS

Pump and treat (P&T) technology involves extracting groundwater from the subsurface through one or more wells and treating the extracted groundwater above ground (*ex situ*). Aboveground treatment systems typically include one or more biological, physical, or chemical technologies for treating the extracted groundwater and one or more technologies for treating any off-gases such as GAC. This section presents a summary of data obtained from case studies of P&T projects and the results of the analysis of those data.

Methodology for Cost Analysis for P&T Projects

In total, 32 case studies addressing 32 individual projects where P&T was the primary technology used to remediate the contaminated media were identified from the available information sources. The case studies, prepared by the FRTR, were obtained from the report *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, February 2001.

Capital and operating costs were obtained from the case studies, along with data needed to calculate unit costs. Exhibit 6-1 presents summary information about the 32 projects for which fully-defined cost data were available, including site name and location, contaminants, technology design, and costs.

The majority of the case studies are ongoing P&T projects for which cost data were provided only for a specified period of operation. Neither the total cost nor the total length of time to complete the project was specifically known or identified in the case studies. Therefore, this analysis presents the average annual costs rather than the total annual costs incurred during site remediation, and no net present value (NPV) was calculated.

Exhibit 6-2 provides a summary of the cost data presented in Exhibit 6-1 for total capital cost, average operating cost per year, and unit costs (unit capital and unit average annual operating cost). To illustrate the range of costs, the 25th percentile, 50th percentile (median), 75th percentile, and average are presented for each cost category. The median total capital cost was $2,000,000, and the median average operating cost per year was $260,000. Several factors affect the average operating cost per year, including throughput of the system and the treatment processes required to treat the extracted groundwater, as well as the operating efficiency of the system. Since no breakdown of annual operating costs by year was available for most projects, the change in operating costs over the life of a remediation system could not be evaluated.

As discussed above, for the majority of projects, which are ongoing, no total project cost (capital plus operating costs) was provided in the case studies, or no such cost could be calculated. However, information was available for total capital cost and average annual operating cost. That information was used to calculate unit costs in terms of (1) a unit capital cost per volume of groundwater treated and (2) a unit average annual operating cost per volume of groundwater treated. The volume of groundwater treated is expressed in terms of 1,000 gallons per year, reflecting the way in which the case studies typically reported quantity treated (as a rate in terms of gallons per minute or gallons per year). In addition, the total volume of groundwater treated was not known or could not be calculated for ongoing projects.

- ***Unit Capital Cost (Capital Cost per 1,000 Gallons of Groundwater Treated per Year) -*** This value was calculated by dividing the total capital cost by the average quantity of groundwater treated each year. This value represents the relative costs of installing P&T systems of various sizes and complexities.

- ***Unit Average Annual Operating Cost (Average Annual Operating Cost per 1,000 Gallons of Groundwater Treated per Year) -*** This value was calculated by dividing the average operating cost per year of operation by the average quantity of groundwater treated per year. This value represents the relative costs of operating P&T systems of various sizes and complexities.

Exhibit 6-1. Summary of Information for P&T Sites with Fully Defined Cost Data (Page 1 of 4)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1,2]	Type of *ex situ* treatment) [3]					Years of Operation/Status [4]	Average Gallons Treated Per Year (1,000 Gallons)	Total Capital Cost ($) [5]	Average Annual Operating Cost ($) [6]	Unit Capital Cost (Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year) [5]	Unit Average Annual Operating Cost (Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated
		BIO	GAC	PHYS/CHEM	OXID	STRIP						
CHLORINATED SOLVENTS ALONE OR WITH OTHER VOCS												
French, Ltd., TX	Benzene, toluene, chloroform, 1,2-DCA, VC	●	●	●			3.9/A	78,000	16,000,000	3,200,000	$200	$41
TCAAP, MN	1,2-DCE, 1,1,1-TCA, TCE, PCE					●	4.9/O	1,400,000	12,000,000	810,000	$8.4	$0.58
Firestone, CA	1,1-DCE, TCE, PCE, 1,1-DCA, benzene, toluene, xylene		●			●	6.8/C	270,000	6,900,000	2,000,000	$26	$7.3
McClellan AFB, OU B/C, CA	None, primary contaminants of concern are TCE, cis-1,2-DCE, PCE, 1,2-DCA					●	6.8/O	96,000	5,600,000	1,600,000	$58	$17
DOE, Savannah River, SC	TCE, PCE, 1,1,1-TCA					●	8.3/O	240,000	5,200,000	170,000	$21	$0.71
Des Moines, IA	TCE					●	8.8/O	550,000	2,200,000	140,000	$3.9	$0.25
Old Mill, OH	TCE, PCE, 1,2-DCE, ethylbenzene		●			●	7.8/O	1,700	2,100,000	240,000	$1,300	$150
Sol Lynn, TX	TCE		●	●		●	3.0/S	4,000	2,000,000	130,000	$460	$31
U.S. Aviex, MI	1,1,1-TCA, 1,2-DCA, DEE, 1,1-DCE, TCE, PCE, BTEX					●	3.4/O	96,000	1,900,000	230,000	$20	$2.4
DOE, Kansas City, MO	None; contaminants of greatest concern at the site are PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, and VC.				●		5.8/O	11,000	1,900,000	450,000	$170	$40
Keefe, NH	PCE, TCE, 1,1-DCE, benzene, 1,2-DCA			●		●	4.1/O	11,000	1,900,000	280,000	$170	$25
SCRDI Dixiana, SC	PCE, TCE, 1,1,1-TCA, 1,1-DCE, 1,1,2-TCA, 1,1,2,2-PCA, chloroform, carbon tetrachloride, benzene, dichloromethane					●	4.6/O	4,500	1,900,000	220,000	$420	$48
JMT, NY	TCE, cis-1,2-DCE, TCA, VC					●	9.6/O	5,200	1,400,000	220,000	$280	$42

Exhibit 6-1. Summary of Information for P&T Sites with Fully-Defined Cost Data
(Page 2 of 4)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1,2]	Type of *ex situ* treatment) [3]					Years of Operation/Status [4]	Average Gallons Treated Per Year (1,000 Gallons)	Total Capital Cost ($) [5]	Average Annual Operating Cost ($) [6]	Unit Capital Cost (Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year) [5]	Unit Average Annual Operating Cost (Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated
		BIO	GAC	PHYS/CHEM	OXID	STRIP						
City Industries, FL	1,1-DCA, 1,1-DCE, MC, VC, PCE, TCE, 1,1,1-TCA, benzene, toluene, ethylbenzene, acetone, MEK, MIBK, phthalates, cis-1,2-DCE, trans-1,2-DCE					●	3.0/O	51,000	1,200,000	160,000	$23	$3.2
Solid State, MO	TCE					●	4.2/O	62,000	1,000,000	300,000	$17	$4.9
Intersil (P&T), CA	TCE, cis-1,2-DCE, VC, Freon 113®					●	7.2/D	5,000	510,000	200,000	$100	$41
Mystery Bridge, WY	trans-1,2-DCE, cis-1,2-DCE, TCE, PCE, 1,1,1-TCA, 1,1-DCE					●	3.6/O	54,000	340,000	180,000	$6.3	$3.4
Gold Coast, FL	MC, 1,1-DCA, trans-1,2-DCE, TCE, PCE, toluene					●	3.7/C	22,000	290,000	130,000	$13	$6.2
BTEX ONLY												
Site A, NY	BTEX					●	2.3/O	6,700	2,200,000	430,000	$330	$65
Amoco, MI	None, contaminants of concern are BTEX and MTBE		●				5.7/O	150,000	470,000	700,000	$3.2	$4.7
METALS ONLY												
United Chrome, OR	Cr			●			8.6/O	7,200	5,100,000	110,000	$710	$15
Odessa I, TX	Cr			●			4.2/O	30,000	1,900,000	220,000	$62	$7.5
Odessa II, TX	Cr			●			4.1/O	30,000	1,800,000	160,000	$62	$5.4
OTHER COMBINATIONS OF CONTAMINANTS												
Western Processing, WA	Cd, Cr, Cu, Ni, Pb, Zn, Hg, Ag, cyanide, trans-1,2-DCE, cis-1,2-DCE					●	8.2/O	120,000	19,000,000	4,600,000	$160	$39
Baird and McGuire, MA	BTEX, acenaphthene, naphthalene, 2,4-dimethyl phenol, dieldrin, chlordane, Pb, As		●	●		●	3.8/O	21,000	15,000,000	2,500,000	$730	$120

Exhibit 6-1. Summary of Information for P&T Sites with Fully-Defined Cost Data
(Page 3 of 4)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1,2]	Type of *ex situ* treatment) [3]					Years of Operation/Status [4]	Average Gallons Treated Per Year (1,000 Gallons)	Total Capital Cost ($) [5]	Average Annual Operating Cost ($) [6]	Unit Capital Cost (Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year) [5]	Unit Average Annual Operating Cost (Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated
		BIO	GAC	PHYS/CHEM	OXID	STRIP						
Bofors Nobel, OU 1, MI	Remedial goals set for analine, 2-chloroaniline, selected purgeable halocarbons, and selected purgeable aromatics; key specific contaminants are benzene, benzidine, 2-chloroaniline, 1,2-DCE, TCE, 3,3-dichlorobenzidene, aniline, VC.		●		●	●	3.1/O	230,000	16,000,000	970,000	$70	$4.3
Sylvester/ Gilson Road, NH	MC, chloroform, MEK, toluene, phenols, Se, methyl methacrylate, 1,1,1-TCA, trans-1,2-DCA, 1,1-DCA, chlorobenzene, 1,1,2-TCA, VC, benzene	●		●		●	9.5/E	130,000	11,000,000	2,400,000	$85	$19
LaSalle, IL	PCBs, TCE, 1,2-DCE, 1,1,1-TCA, VC, 1,1-DCA, PCE		●			●	4.4/O	5,200	7,400,000	210,000	$1,400	$40
Solvent Recovery Service, CT	None; contaminants at the site include TCE, cis-1,2-DCE, 1,1,1-TCA, PCBs, Ba, Cd, Ch, Pb, Mn		●	●	●		3.0/O	11,000	5,100,000	660,000	$470	$61
Libby, MT	Napthalene, acenaphthene, fluorene, anthracene, pyrene, fluoranthene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, indeno(1,2,3-cd)pyrene, As, benzene, PCP	●					5.3/O	3,000	4,300,000	520,000	$1,500	$180
King of Prussia, PA	1,1-DCA, trans-1,2-DCE, 1,1,1-TCA, TCE, PCA, PCE, benzene, toluene, ethylbenzene, Be, Cr, Cu, Ni, Cd, Hg, Zn		●	●		●	2.7/O	57,000	1,800,000	290,000	$32	$5.1

Exhibit 6-1. Summary of Information for P&T Sites with Fully-Defined Cost Data (Page 4 of 4)

Site Name and Location	Contaminants With Remedial Cleanup Goals [1,2]	Type of *ex situ* treatment) [3]					Years of Operation/Status [4]	Average Gallons Treated Per Year (1,000 Gallons)	Total Capital Cost ($) [5]	Average Annual Operating Cost ($) [6]	Unit Capital Cost (Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year) [5]	Unit Average Annual Operating Cost (Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated
		BIO	GAC	PHYS/CHEM	OXID	STRIP						
MSWP, AR	PCP, Cr, As, benzo(a)anthracene, benzo(a)pyrene, benzo(b+k)fluoranthene, chrysene		●				8.3/O	12,000	600,000	120,000	$49	$10

Source:

EPA, Office of Solid Waste and Emergency Response, *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, EPA 542-R-00-013, December 2000

Notes:

[1] Most case studies identified multiple contaminants at a site. This table lists those contaminants for which remedial cleanup goals were specified in the case study.

[2] Contaminant Key: As = arsenic, Ba = barium, Be = beryllium, BTEX = benzene, toluene, ethylbenzene, and xylenes, Cd = cadmium, Cr = chromium, Cu = copper, DCA = dichloroethane, DCE = dichloroethene, DEE = diethyl ether, MC = methylene chloride, MEK = methyl ethyl ketone, MIBK = methyl isobutyl ketone, Mn = manganese, MTBE = methyl tert butyl ether, NH-SVOLs = nonhalogenated semivolatiles, Ni = nickel, PAH = polycyclic aromatic hydrocarbons, Pb = lead, PCA = tetrachloroethane, PCB = polychlorinated biphenyls, PCE = tetrachloroethene, PCP = pentachlorophenol, TCA = tetrachloroethane, TCE = tetrachloroethene, VC = vinyl chloride, Zn = zinc.

[3] Remediation Technology Key: AS = air sparging, BIO = biological treatment, FPR = free product recovery, GAC = granular activated carbon adsorption, ISB = *in situ* bioremediation, PHYS/CHEM = physical or chemical removal of metal, OXID = Oxidation, PRB = permeable reactive barrier, STRIP = air stripping, VCB = vertical containment barrier.

[4] Status Key: A = monitored natural attenuation, C = complete, D = P&T discontinued, PRB ongoing, E = shut down pending explanation of significant difference, O = ongoing, S = shut down pending study.

[5] All reported costs were adjusted for location and years during which costs were incurred, as described in the text. All unadjusted (reported) costs are presented in parentheses.

[6] Average annual operating cost was calculated by dividing the total of the operating costs to date, as reported in the case study, by the number of years represented by that cost.

Exhibit 6-2. Summary of Remedial Cost and Unit Cost Data for 32 P&T Sites

Cost Category[1]	25th Percentile	Median	75th Percentile	Average
Total Capital Cost ($)	$1,700,000	$2,000,000	$6,000,000	$4,900,000
Average Operating Cost Per Year ($/Year)[2]	$180,000	$260,000	$730,000	$770,000
Unit Capital Cost (Capital Cost Per 1,000 Gallons of Groundwater Treated Per Year)	$23	$78	$350	$280
Unit Average Annual Operating Cost (Average Annual Operating Cost Per 1,000 Gallons of Groundwater Treated Per Year)	$5	$16	$41	$32

Source: *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, EPA 542-R-00-013, February 2001.

Notes:

[1] All reported costs were adjusted for location and years during which costs were incurred, as described in Section 1.

[2] The average annual operating cost was calculated by dividing the total of operating costs to date, as reported in the case study, by the number of years represented by that cost.

Results

The costs of P&T projects were evaluated to determine whether any correlations were evident in unit cost versus quantity of groundwater treated per year. The analysis was performed for (1) unit capital cost versus volume of groundwater treated per year and (2) unit average annual operating cost versus volume of groundwater treated per year, by calculating reverse exponential linear fits of each data set, as described in Section 1. Exhibits 6-3 and 6-4 present the results of the two analyses on both decimal-scale and logarithmic-scale plots. Appendix B presents the detailed backup for the analyses, including alternate confidence interval calculations.

Unit Capital Cost Versus Volume of Groundwater Treated

As Exhibit 6-3 shows, a correlation between unit capital costs and volume of groundwater treated is evident. Economies of scale were observed where unit costs decreased as larger quantities were treated. For example, unit capital costs decreased from $60 to 800 per 1,000 gallons treated per year for projects treating up to 30 million gallons of groundwater per year to less than $20 per 1,000 gallons treated per year for projects treating relatively larger quantities of groundwater per year.

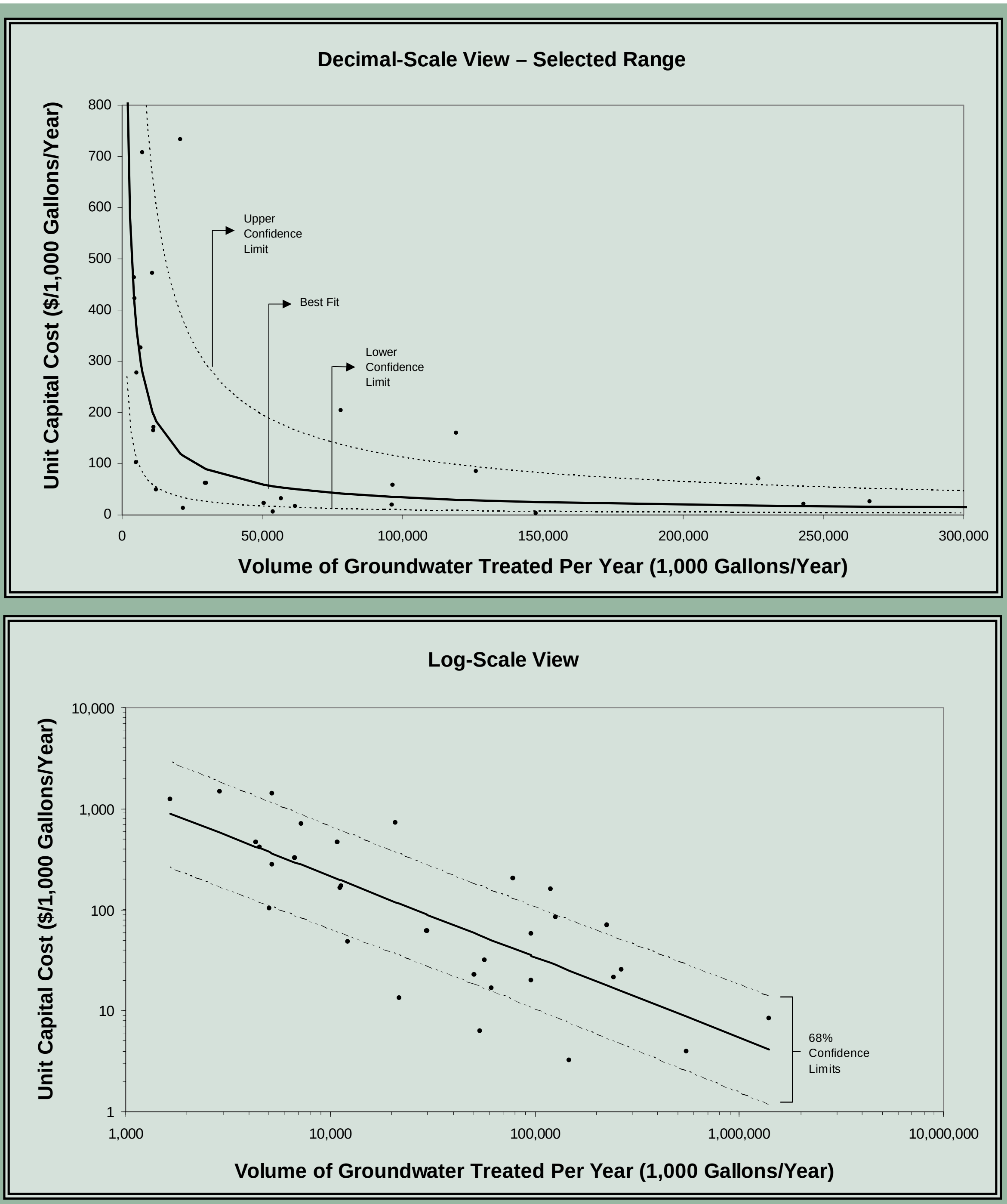
Unit Average Annual Operating Cost Versus Volume of Groundwater Treated

Exhibit 6-4 presents a similar correlation for unit average annual operating cost per volume of groundwater treated per year, with economies of scale observed where unit costs decreased as larger quantities were treated. For example, unit average annual operating costs decreased from $10 to 120 per 1,000 gallons treated per year for projects treating less than 20 million gallons of groundwater per year to less than $1 to $5 per 1,000 gallons of groundwater treated per year for projects treating relatively larger quantities of groundwater per year.

Other Factors

Potential correlations between unit cost and other factors, such as type of contaminant and type of *ex situ* groundwater treatment used, were considered, but no correlations were evident. While quantitative correlations for those factors were not evident, the following qualitative information about potential factors affecting the design and operation of P&T systems was provided in the case studies and in the EPA report *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, February, 2001. The specific effects of those and other factors on the cost of a P&T system are highly site-specific.

Exhibit 6-3. P&T Projects – Unit Capital Cost vs. Volume Treated (with 68-Percent Confidence Interval)



Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 32 pump-and-treat projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which the volume of groundwater treated per year was less than 300 million gallons or the unit capital cost was less than $800 per 1,000 gallons treated per year).

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 59 percent.

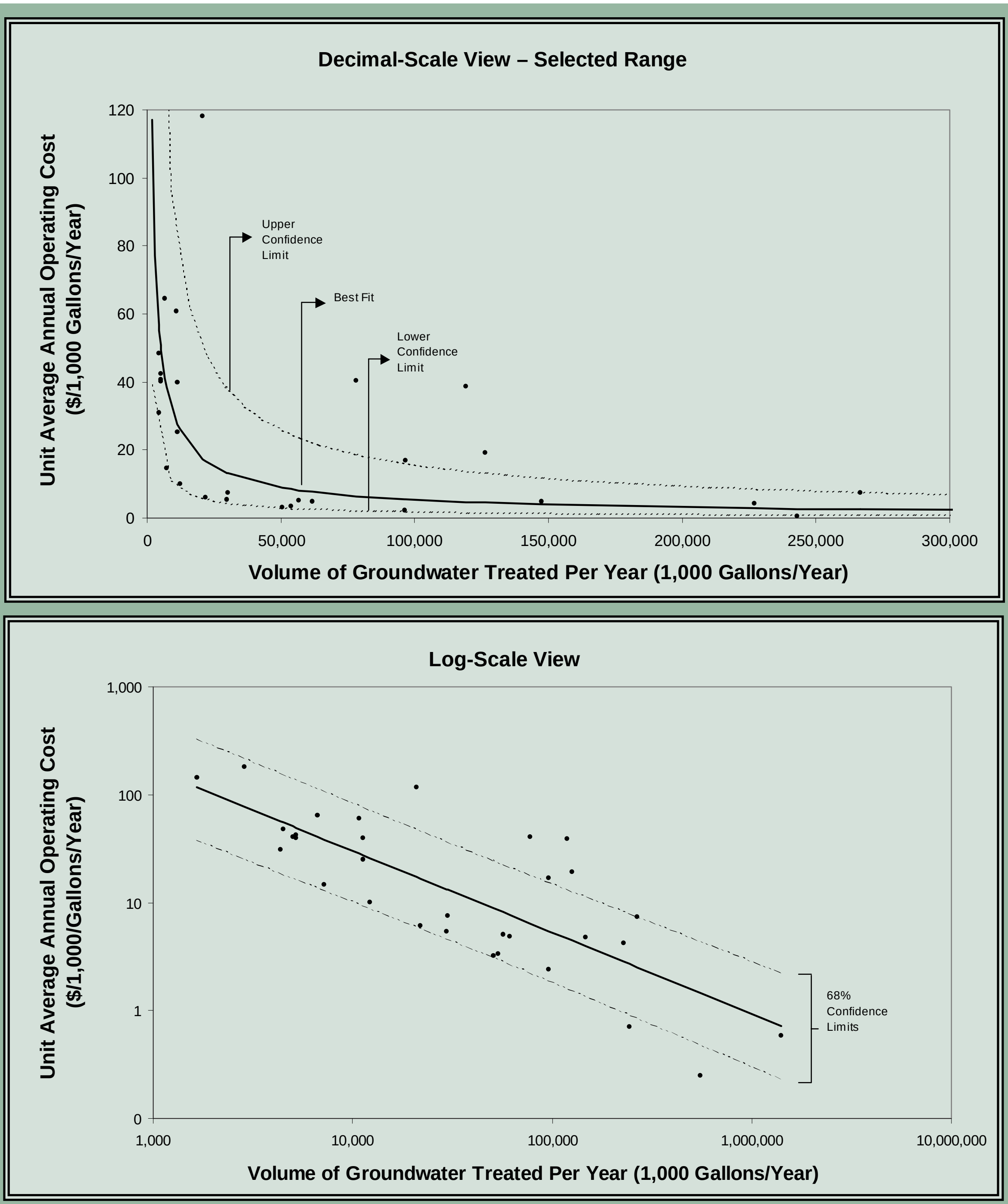
[4] Appendix B presents the methodology and other statistical information related to the above plots.

Soil type and hydrogeologic setting: The permeability, porosity, moisture content, and heterogeneity of the soil and the depth and stratigraphy of the contamination in the subsurface affect the number and placement of the extraction wells, the radius of influence of the extraction wells, and the ease with which contamination can be removed from the subsurface. Properties of the aquifer that define contaminant transport and groundwater extraction system design needs include hydraulic connection of aquifers that allows contamination of more than one aquifer, aquifer flow parameters, influences of adjacent surface-water bodies on the aquifer system, and influences of adjacent groundwater production wells on the aquifer system.

Properties of the contaminant and extent of contamination: The properties and concentration of contaminants, along with the areal extent of the contamination (plume size), affect the size of the extraction system (number and depth of wells and pump size), the type and complexity of the above-ground treatment system, and the need for off-gas treatment. For example, both capital and average annual operating costs tended to be higher for projects where combinations of contaminants (solvents, BTEX, metals, PCBs, or PAHs) were present because more complex systems generally were required to treat complex combinations of contaminants. In general, groundwater contamination concentrated in an isolated area and at a shallow depth typically is easier and less costly to remediate than the same mass of contaminant when it is extended deeper and spread out over a larger area.

Source control: The presence of NAPLs in groundwater can serve as a continuing source of contamination, extending the length of time that it may be necessary to operate to reach cleanup levels. Source controls may be implemented at a site to address the NAPLs, with the type and extent of the NAPL contamination determining the complexity and potential effectiveness of the source control.

Exhibit 6-4. P&T Projects – Unit Average Annual Operating Cost vs. Volume Treated (with 68-Percent Confidence Interval)



Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 32 pump-and-treat projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which the volume treated per year was less than 300 million gallons and the unit average annual operating cost was less than $120 per 1,000 gallons treated per year).

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the linear fit to the data is 62 percent.

[4] Appendix B presents the methodology and other statistical information related to the above plots.

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7.0 PERMEABLE REACTIVE BARRIERS

A permeable reactive barrier (PRB) is an *in situ* treatment zone of reactive material that degrades or immobilizes contaminants as groundwater flows through it. PRBs are installed as permanent, semi-permanent, or replaceable units across the flow path of a contaminant plume. The type of reactive material used for the PRB is determined based on the specific contaminants and the conditions of the aquifer. Examples of reactive materials used in PRBs include zero-valent iron, organic carbon, and limestone. Most PRBs are installed in one of two basic configurations - funnel and gate or continuous trench. This section presents a summary of data obtained from case studies of PRB projects and the results of the analysis of those data.

Methodology for Cost Analysis for PRB Projects

As Exhibit 7-1 shows, 16 PRB case studies addressing 16 individual projects were identified from the available information sources. The case studies, prepared by the FRTR and the Remediation Technology Development Forum (RTDF)[6], were obtained from the report *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, February 2001. PRB projects were identified using the criteria discussed in Section 1 and the following two technology-specific criteria:

- The PRB system was operated on a full-scale basis (as opposed to a pilot-scale or field demonstration project).
- Information was available about the capital cost of the PRB system.

Capital and operating cost data were obtained from the case studies. A review of the information showed that, while capital costs were available for all 16 projects, annual operating costs were available for only two projects. Further, none of the case studies provided information about unit costs or information needed to calculate unit costs such as the quantity of groundwater treated or the mass of contaminant removed. Therefore, it was determined that fully defined cost data, as described in Section 1, were not available for any of the PRB projects. Exhibit 7-1 summarizes available information about the sites, including site name and location, PRB design, and cost data.

Exhibit 7-2 summarizes available capital cost information for the 16 PRB projects by the 25th percentile, 50th percentile (median), 75th percentile, and average to illustrate the range of costs. The median total capital cost of the 16 PRB projects was $680,000.

Results

As discussed in Section 1, fully defined cost data must be available for at least five sites to identify a potential correlation between unit cost and quantity treated. Fully defined cost data were not available for any of the PRB projects because no information about the quantity treated was available. Therefore, no quantitative analyses of unit cost versus quantity treated was performed.

Potential correlations between unit cost and other factors, such as type of contaminant, were considered, but no correlations were evident. While no quantitative correlations for those factors were evident, the following qualitative information about potential factors affecting the design and operation of PRB systems was provided in the case studies; in the EPA report *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, February, 2001; and in the report *Permeable Reactive Barriers Notebook*. The specific effects of those and other factors on the cost of a PRB system are highly site-specific.

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[6] The RTDF includes members representing industry, government, and academia who have an interest in identifying steps government and industry can take together to develop and improve the environmental technologies needed to address their mutual cleanup problems in the safest, most cost-effective manner possible. Information about the RTDF is available through the organization's web site at <*www.rtdf.org*>. Case studies are available in *Field Applications of In Situ Remediation Technologies: Permeable Reactive Barriers*, EPA 542-R-99-002, 1999.

Exhibit 7-1. Summary Information for PRB Sites
(Page 1 of 4)

Site Name and Location	Contaminants[1]	Capital Cost ($)[2]	Cost Components						Installation Date	Installation Method[3]	Number of PRBs/Gates	PRB Location or Function	Reactive Medium Material[4]	Dimensions of Reactive Medium			
			Design	Construction	Materials	Reactive Media	Engineering	Unspecified						Total Mass	Width	Length	Depth
CHLORINATED SOLVENTS																	
Kansas City Plant, MO	1,2-DCE, VC	1,600,000 Design = 200,000 Other = 1,300,000	●	●	●	●			Apr. 1998	CT	1	Top half of trench	2 ft Fe^{o}, 4 ft sand	370 tons of iron	6 ft	130 ft	13-27 ft
												Bottom half of trench	100% Fe^{o}				27-33 ft
Caldwell Trucking, NJ	TCE	1,400,000	●	●	●	●			Apr. 1998	HF	2	Permeation infill	Fe^{o}	250 tons	3 in	150 ft	15-50 ft
												Hydrofrace	Fe^{o}		3 in	90 ft	15-50 ft
Former Manufacturing Site, NJ	1,1,1-TCA; PCE; TCE; DNAPL	1,100,000 Design = 180,000 Iron = 360,000 Other = 560,000	●	●	●	●			Sept. 1998	DE, CT, SPC	1	DNAPL excavation	1:1 Fe^{o}/sand	720 tons of iron	5 ft	127 ft	25 ft
												Top 4 to 7 ft of CT	3:2 Fe^{o}/sand				
												Bottom 7 to 21 ft of CT	4:1 Fe^{o}/sand				
FHA Facility, CO	TCA; 1,1-DCE; TCE; cis-1,2-DCE	1,100,000 Iron = 210,000 Other = 890,000	●	●	●	●			Oct. 1996	F&G	4	All 4 PRBs	Fe^{o}	476 tons of iron	varies	Each gate is 40 ft wide	25 ft
Industrial Site, NY	TCE, cis-1,2-DCE, VC	1,000,000 Iron = 360,000 Other = 640,000		●	●	●			Dec. 1997	CT	2	Main trench	Fe^{o}	742 tons	1 ft	370 ft	18 ft
												Upgradient trench			1 ft	10 ft	NR

Exhibit 7-1. Summary of Information for PRB Sites
(Page 2 of 4)

Site Name and Location	Contaminants[1]	Capital Cost ($)[2]	Cost Components						Installation Date	Installation Method[3]	Number of PRBs/Gates	PRB Location or Function	Reactive Medium Material[4]	Dimensions of Reactive Medium			
			Design	Construction	Materials	Reactive Media	Engineering	Unspecified						Total Mass	Width	Length	Depth
Intersil, CA[5]	TCE, cis-1,2-DCE, VC, Freon 113®	760,000 Iron = 170,000 Other = 590,000		●	●	●			Feb. 1995	F&G	1	NA	Fe^o	220 tons	4 ft	36 ft	11-31 ft
Aircraft Facility, OR	TCE	710,000						●	Mar. 1998	F&G	2	Gate 1	Fe^o	324 tons of iron*	Two 9-in thick layers	50 ft	to 24-34 ft
												Gate 2	Fe^o, sand		3 ft	60 ft	to 24-34 ft
Lowry Air Force Base, CO	TCE	600,000	●	●	●	●			Dec. 1995	F&G	1	NA	Fe^o	NR	5 ft	10 ft	0-17 ft
Industrial Site, N. Ireland	TCE; cis-1,2-DCE	580,000		● *	●	●	●		Dec. 1995	F&R	1	NA	Fe^o	NR	Vessel has 4-ft diam.	Vessel has 4-ft diam.	33-49 ft
Industrial Site, KS	TCE; 1,1,1-TCA	400,000 Iron = 50,000 Other = 350,000		● *	●	●			Jan. 1996	F&G	1	NA	Fe^o	70 tons	3 ft	20 ft	0-30 ft
Industrial Site, SC	TCE, cis-1,2-DCE, VC	360,000 Design = 45,000 Iron = 130,000 Other = 180,000	●	●	●	●			Nov. 1997	CT	1	NA	Fe^o, sand (1:1 ratio)	400 tons of iron	1 ft	375 ft*	0-29 ft

Exhibit 7-1. Summary of Information for PRB Sites
(Page 3 of 4)

Site Name and Location	Contaminants[1]	Capital Cost ($)[2]	Cost Components						Installation Date	Installation Method[3]	Number of PRBs/Gates	PRB Location or Function	Reactive Medium Material[4]	Dimensions of Reactive Medium			
			Design	Construction	Materials	Reactive Media	Engineering	Unspecified						Total Mass	Width	Length	Depth
Former Dryclean Site, Germany	PCE; 1,2-DCE	160,000 Design = 39,000 Other = 120,000	●	●		●			June 1998	CW	1	NS	1:1 mass ratio Fe^o/ gravel	69 tons	2-3 ft	33 ft	10 - 33 ft[6]
												NS	IS	85 tons		41 ft	
METALS AND INORGANICS																	
Nickel Rim Mine Site, Canada	Ni, Fe, Sulfate	43,000	●	●	●	●			Aug. 1995	C&F	1	NA	OC/ pea gravel	NR	12 ft	50 ft	14 ft deep
COMBINATION OF CONTAMINANTS																	
Y-12 Site, Oak Ridge National Lab, TN	U, Tc, HNO3	1,900,000	●	●	●	●			Nov. 1997	CT	1	NS	100% iron	80 tons iron	2 ft	26 ft	22-30 ft
												NS	100% gravel	NR		199 ft	
									Dec. 1997	F&R	5	All 5 reactors	iron	NR	NR	NR	NR
Marzone Inc., GA	alpha-HCB, beta-HCB, DDD, DDT, xylene, EB, lindane, methyl parathion	650,000 Design = 200,000 Other = 450,000	●	●	●	●			Aug. 1998	F&G	1	NA	AC	0.9 tons	NR	NR	NR

Exhibit 7-1. Summary of Information for PRB Sites
(Page 4 of 4)

Site Name and Location	Contaminants [1]	Capital Cost ($) [2]	Cost Components						Installation Date	Installation Method [3]	Number of PRBs/Gates	PRB Location or Function	Reactive Medium Material [4]	Dimensions of Reactive Medium			
			Design	Construction	Materials	Reactive Media	Engineering	Unspecified						Total Mass	Width	Length	Depth
U.S. Coast Guard Support Center, NC[7]	Cr^{+6}, TCE	460,000 Design = 160,000 Iron = 150,000 Other = 150,000	●	●	●	●			June 1996	CT	1	NA	Fe^o	450 tons	2 ft	150 ft	3-24 ft

Source: EPA, Office of Solid Waste and Emergency Response, *Cost Analyses for Selected Groundwater Cleanup Projects: Pump and Treat and Permeable Reactive Barriers*, EPA 542-R-00-013, December 2000.

Notes:

[1] Contaminant Key: As = arsenic, HCB = hexachlorobenzene, Cd = cadmium, Cu = copper, Cr^{+6} = hexavalent chromium, DCE = dichloroethene, DDD = dichlorodiphenyldichloroethane, DDT = dichlorodiphenyltrichloroethane, DNAPL = dense non-aqueous-phase liquid, EB = ethylbenzene, Fe = Iron, HNO3 = nitric acid, Ni = Nickel, Pb = lead, PCE = tetrachloroethene, Tc = technetium, TCA = trichloroethane, TCE = trichloroethene, U = uranium, VC = vinyl chloride, Zn = zinc.

[2] All reported capital costs were adjusted for site locations and years when costs were incurred, as described in the text. All unadjusted (reported) costs are presented in parentheses. Adjusted costs are not presented in parentheses.

[3] Installation Method Key: C&F = cut and fill, CT = continuous trencher, CW = continuous wall, DE = dense nonaqueous-phase liquid (DNAPL) extraction, F&G = funnel and gate, F&R = funnel and reaction vessel, HF = hydraulic fracturing, SPC = Sheet piling construction.

[4] Reactive Media Material Key: AC = activated carbon, AFO = amorphous ferric oxyhydroxide, Fe^o = zero-valent iron, IS = iron sponge (wood shavings or chips impregnated with hydrated iron oxide), LM = limestone, OC = organic carbon (municipal/leaf compost and wood chips), PO_4 = bone char phosphate.

NA = Not applicable, NR = Not reported, NS = Not specified

Exhibit 7-2. Summary of Remedial Cost Data for 16 PRB Sites

Cost Category	PRB Sites (16 Sites)			
	25th Percentile ($)	**Median ($)**	**75th Percentile ($)**	**Average ($)**
Total Capital Cost ($)[1]	440,000	680,000	1,000,000	730,000

Source: FRTR and RTDF - Refer to Exhibit 7-1 for a list of sites.

Notes:

[1] All reported costs were adjusted for location and years during which costs were incurred, as described in Section 1.

Hydrogeologic setting: Because a PRB relies on the natural gradient of the groundwater to allow the plume to move through the reactive zone, the groundwater flow patterns and distribution of the contaminants in the plume (location and extent) are important considerations in the installation of a PRB. Those conditions are influenced by such parameters as the piezeometric surfaces and gradient, hydraulic conductivity, permeability, and porosity (which may vary stratigraphically), and seasonal variation in groundwater flow direction and flux. The depth of the aquifer and of the contamination, whether the aquifer is unconfined or confined, and the chemistry of the aquifer also influence the design of the PRB, including location and configuration (funnel and gate or continuous trench), size, and whether and how the PRB is keyed into the subsurface (for example, keyed into a low-permeability clay layer to prevent underflow of the contaminant).

Geochemistry: Geochemical parameters of the aquifer or plume, such as pH, oxygen content, presence of reducing agents (for example, sulfates), affect the type of reactive media used and the life expectancy of the media. Potential reactions of the specific reactive media with the geochemical properties of the groundwater also may affect the ability of the reactive media to degrade, sorb, precipitate, or otherwise remove contaminants from the groundwater. For example, as groundwater containing carbonate passes through a PRB containing zero-valent iron, calcite ($CaCO_3$) precipitates. Should carbonate levels in the groundwater be high, the resultant precipitate may build up on the reactant surface and reduce the effectiveness of the PRB .

Properties of the contaminant and extent of contamination: Properties of the contaminants, their concentrations, and degradation rates in the presence of the reactive media affect the type of reactive media used, the thickness of the reactive zone and the residence time, the effectiveness of the reactive media, and the life of the reactive media. In addition, the extent of the plume (including variations in types and concentrations of contaminants throughout the plume) affects the placement and orientation of the PRB to capture and treat the entire plume.

Source control: The presence of NAPLs in groundwater can serve as a continuing source of contamination, extending the length of time during which it is necessary to operate a system to reach cleanup levels. Source controls may be implemented at site to address the NAPLs, with the type and extent of the NAPL contamination determining the complexity and potential effectiveness of the source control.

8.0 REFERENCES

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APPENDIX A
Summary of Price Information from the U.S. Army Corps of Engineers for Off-Site Disposal and Off-Site Incineration

In March 1998, the United States Army Corps of Engineers (USACE) published a document titled *Report on Treatment, Storage, and Disposal Facilities (TSDFs) for Hazardous, Toxic, and Radioactive Waste*(*http://www.environmental.usace.army.mil*) that contains information about prices charged by off-site hazardous waste landfills and incineration facilities permitted under RCRA for the disposal of RCRA hazardous wastes. This appendix provides a summary of information obtained from that report that may be useful in comparing costs of other technologies, such as those in the *Remediation Technology Cost Compendium - Year 2000*.

USACE collected the price information by contacting treatment, storage, and disposal facilities (TSDFs) (using a list developed by EPA and state environmental agencies) to obtain vendor price quotes. Price information was obtained for two types of landfills - those that accept bulk solid waste that does not require stabilization and those that accept bulk solid waste that does require stabilization by the TSDF. As Exhibit A-1 shows, price information was obtained for 28 off-site RCRA-permitted facilities - 12 hazardous waste landfills without stabilization; 10 hazardous waste landfills with stabilization; and six hazardous waste incinerators.

For this compendium, the USACE cost data (vendor price quotes) were adjusted for location and inflation, as described in Section 1 of the compendium. Costs also were adjusted to include all applicable taxes and fees for the state in which the vendor was located because, for off-site disposal, taxes and fees are a standard part of the total cost of disposal and vary by location. For example, taxes and fees range from $0 per ton in Louisiana and Indiana to $45.13 per ton in California and $135 per ton in Oregon. Information about taxes and fees was taken directly from the USACE report. Transportation costs were not included in the analysis because such costs are site-specific and generally are considered on a case-by-case basis.

Exhibit A-1 presents a summary of the adjusted price data for the three types of off-site disposal facilities. Data are shown as the 25th percentile, 50th percentile, 75th percentile, and average prices, expressed as cost per ton of waste disposed. The average price ranged from $155 per ton for RCRA hazardous waste disposed of without stabilization at a landfill to $529 per ton for RCRA hazardous waste disposed of by incineration. A number of factors potentially affect the price of waste disposal at such facilities. Example factors include the total quantity of waste being disposed of, the types and concentrations of contaminants in the waste, the physical properties of the waste (for example, particle size, moisture content, and halogen content), and market factors.

Exhibit A-1. Summary of Adjusted USACE Price Data for Off-Site Disposal and Off-Site Incineration of RCRA Hazardous Waste

Type of RCRA Off-Site Disposal Facility	25th Percentile ($/ton)	50th Percentile (Median) ($/ton)	75th Percentile ($/ton)	Average ($/ton)	Number of Facilities
RCRA Hazardous Waste Landfill (without stabilization)	112	143	168	155	12
RCRA Hazardous Waste Landfill (with stabilization)	196	217	283	239	10
RCRA Hazardous Waste Incinerator	472	494	587	529	6

Source: USACE, *Report on Treatment, Storage, and Disposal Facilities for Hazardous, Toxic, and Radioactive Waste*, March 1998.

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APPENDIX B
Additional Information about Development of the Cost Curves

Section 1 of the *Remediation Technology Cost Compendium - Year 2000* summarized the manner in which the cost curves were developed for the compendium. This appendix provides additional information about the statistical analyses used in developing the cost curves, including detailed backup calculations. In addition, at the end of this appendix is a brief response to selected external reviewer comments about the statistical methodology.

The specific steps used in the statistical methodology were:

1. Data on unit cost and quantity of material treated or mass of contaminant removed was transformed to the corresponding natural log values.

2. A linear best fit of the log-transformed data was determined, and a statistical summary of the fit was prepared, including the coefficient of determination (r^2) that was used as a measure of how well the data fit the model.

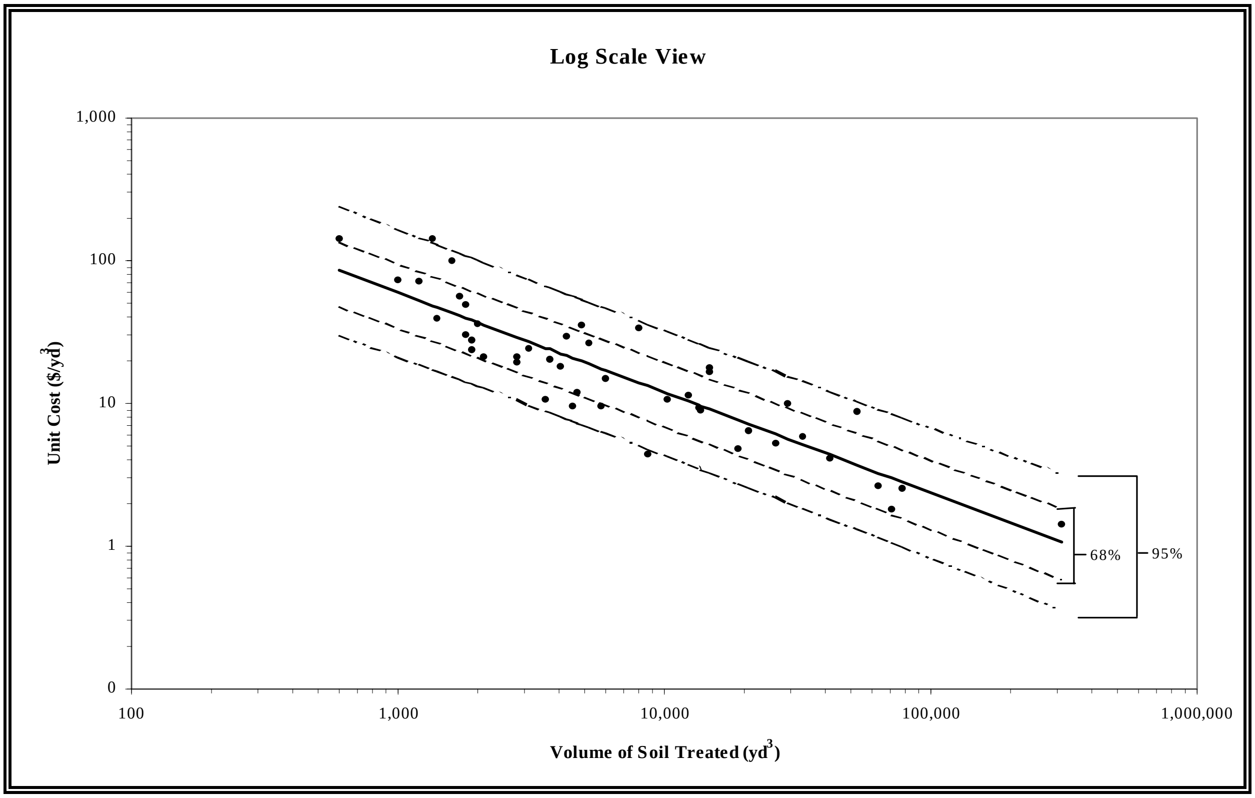
3. Using the log-transformed data, the residuals from the linear fit were examined to determine whether they were distributed normally, using the Shapiro-Wilk W test (a goodness-of-fit test). For this test, the null hypothesis (Ho) is that the data are distributed normally. If the probability of obtaining a smaller value for the Shapiro-Wilk test than the value calculated for the observed data (W) is greater than 0.05, then H_o is not rejected and it is concluded that the data are normally distributed.

4. The line of best fit and both 68- and 95-percent confidence limits for the individual predicted values from the linear regression equation were plotted. Separate plots were also prepared using scales in original units by back transformation of the log-transformed data.

As discussed in the Executive Summary of the compendium, the approach for developing the cost curves, using a reverse exponential model, was tested using the Air Force bioventing cost data for 45 projects. Those data provided the greatest number of technology applications having similar characteristics and represented a comprehensive effort to collect costs at a number of sites by standard procedures. For the bioventing cost curves, the coefficient of determination for the linear fit of the log-transformed data was 0.80, meaning that 80 percent of the variability in the data is explained by the model. The same methodology was applied to other data sets, and the coefficient of determination and other statistical details are provided together with the plots in this appendix. The coefficient of determination varied by technology.

All statistical tests were performed using JMP® (SAS Institute, Inc.) software. Statistical output from JMP is not rounded to a fixed number of significant digits. The results of those calculations are provided for each cost curve.

Exhibit B-1. AFCEE Bioventing Projects – Unit Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)



Notes:

[1] The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 45 bioventing projects are shown in the plots above.

[2] All reported costs were adjusted for site locations, as described in the text.

[3] The coefficient of determination (r^2) for the line of best fit is 80 percent.

Detailed Calculations for AFCEE Bioventing Projects – Unit Cost vs. Volume Treated

Linear Fit

log(Cost/CY) = 8.9310144 - 0.7002108 log(CY)

Summary of Fit

RSquare	0.799508
RSquare Adj	0.794845
Root Mean Square Error	0.494289
Mean of Response	2.760522
Observations (or Sum Wgts)	45

Analysis of Variance

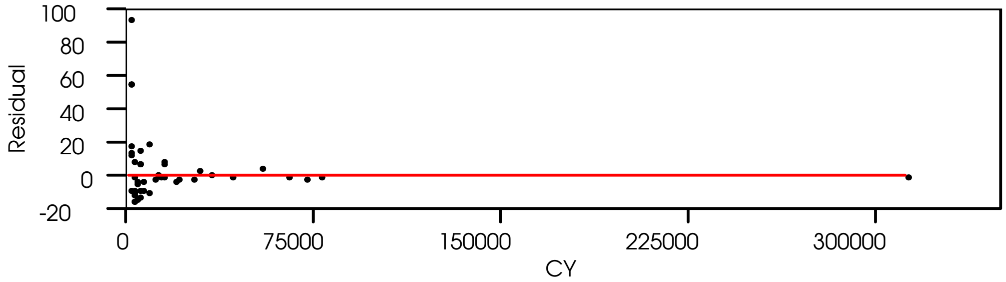
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	41.894246	41.8942	171.4720
Error	43	10.505814	0.2443	**Prob > F**
C. Total	44	52.400060		<.0001

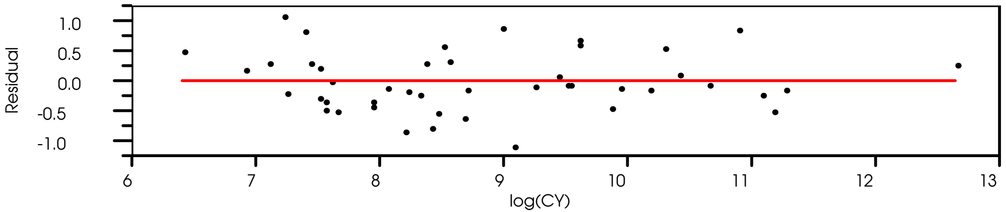
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8.9310144	0.476946	18.73	<.0001
log(CY)	-0.700211	0.053473	-13.09	<.0001

Fit Measured on Original Scale

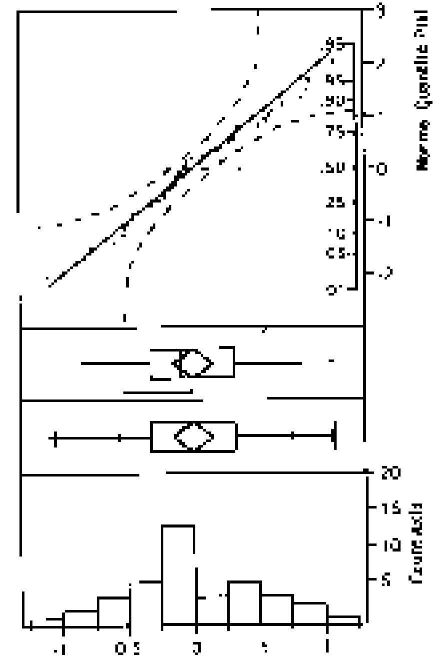
Sum of Squared Error	18372.596
Root Mean Square Error	20.670503
RSquare	0.6044654
Sum of Residuals	194.95537





Distributions

Residuals log(Cost/CY)



Quantiles

100.0%	maximum	1.3791
99.5%		1.3791
97.5%		1.0500
90.0%		0.7424
75.0%	quartile	0.3131
50.0%	median	-0.0911
25.0%	quartile	-0.3279
10.0%		-0.5663
2.5%		-1.0529
0.5%		-1.0512
0.0%	minimum	[illegible]

Moments

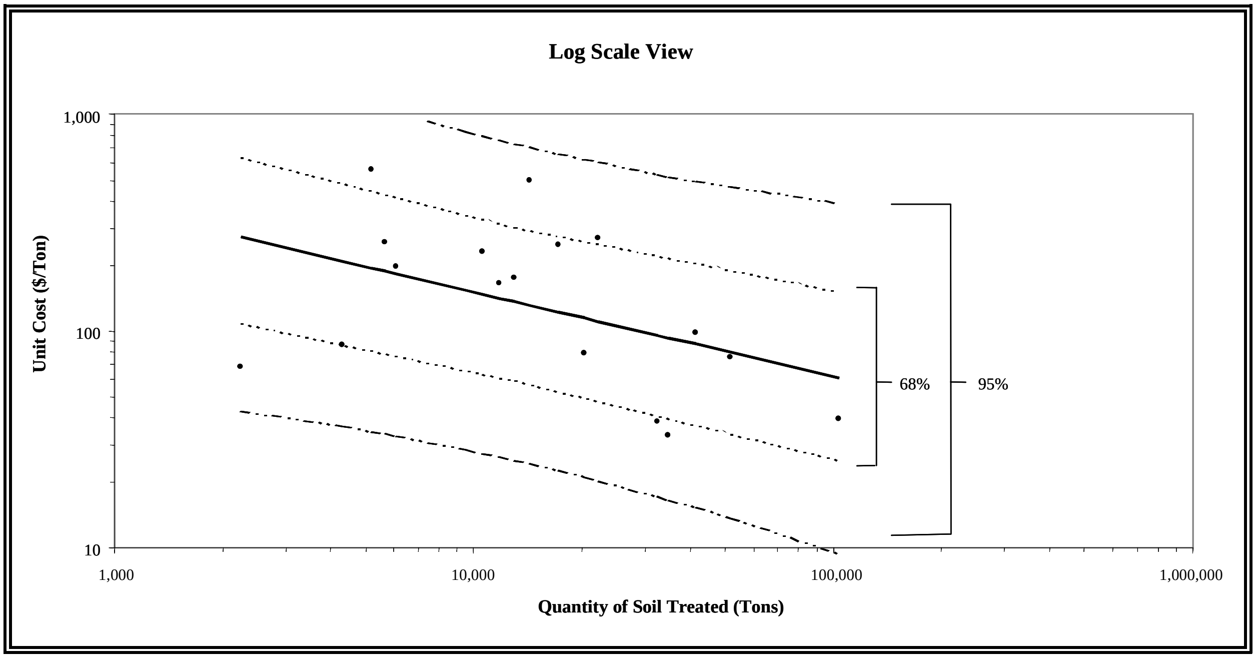
Mean	1.5e-15
Std Dev	0.4886394
Std Err Mean	0.0728421
upper 95% Mean	0.1468033
lower 95% Mean	-0.1468033
N	45
Sum Wgts	45
Sum	[illegible]
Variance	0.2387685
Skewness	0.3053093
Kurtosis	-0.735874
CV	[illegible]

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.979109	0.7761

Exhibit B-2. Thermal Desorption Projects – Unit Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)



Notes:

[1] The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 17 thermal desorption projects are shown in the plots above.

[2] All reported costs were adjusted for location and time, as described in the text.

[3] The coefficient of determination is (r^2) for the line of best fit is 21 percent.

Detailed Calculations for Thermal Desorption – Unit Cost vs. Volume Treated

Linear Fit

log(Cost/Tons) = 8.6166802 - 0.389974 log(Tons)

Summary of Fit

RSquare	0.206222
RSquare Adj	0.156611
Root Mean Square Error	0.772762
Mean of Response	4.881348
Observations (or Sum Wgts)	18

Analysis of Variance

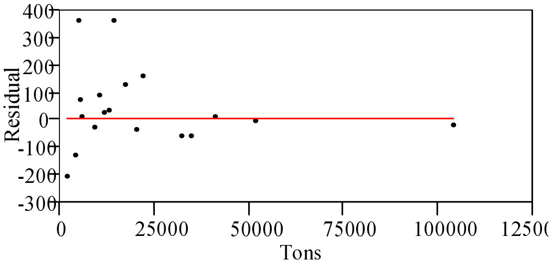
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2.482265	2.48226	4.1568
Error	16	9.554577	0.59716	**Prob > F**
C. Total	17	12.036842		0.0583

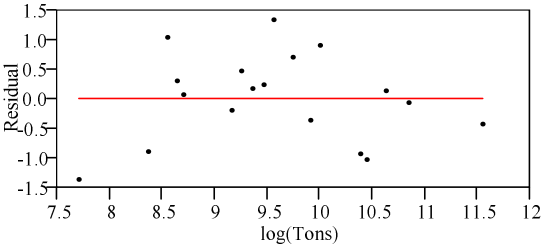
Parameter Estimates

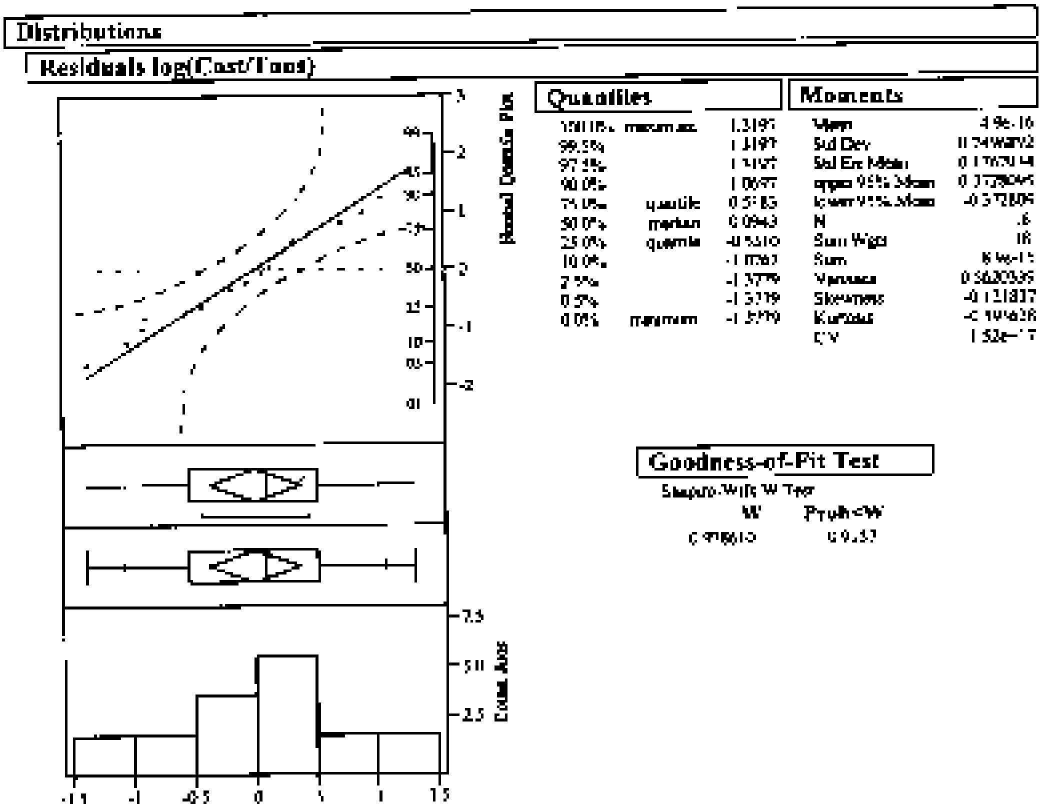
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8.6166802	1.841139	4.68	0.0003
log(Tons)	-0.389974	0.191275	-2.04	0.0583

Fit Measured on Original Scale

Sum of Squared Error	385259.03
Root Mean Square Error	155.1731
RSquare	-0.017582
Sum of Residuals	714.62713







Quantiles

100.0%	maximum	1.3197
99.5%		1.3197
97.5%		1.3197
90.0%		1.0697
75.0%	quartile	0.5183
50.0%	median	0.0943
25.0%	quartile	-0.5510
10.0%		-1.0363
2.5%		-1.3779
0.5%		-1.3779
0.0%	minimum	-1.3779

Moments

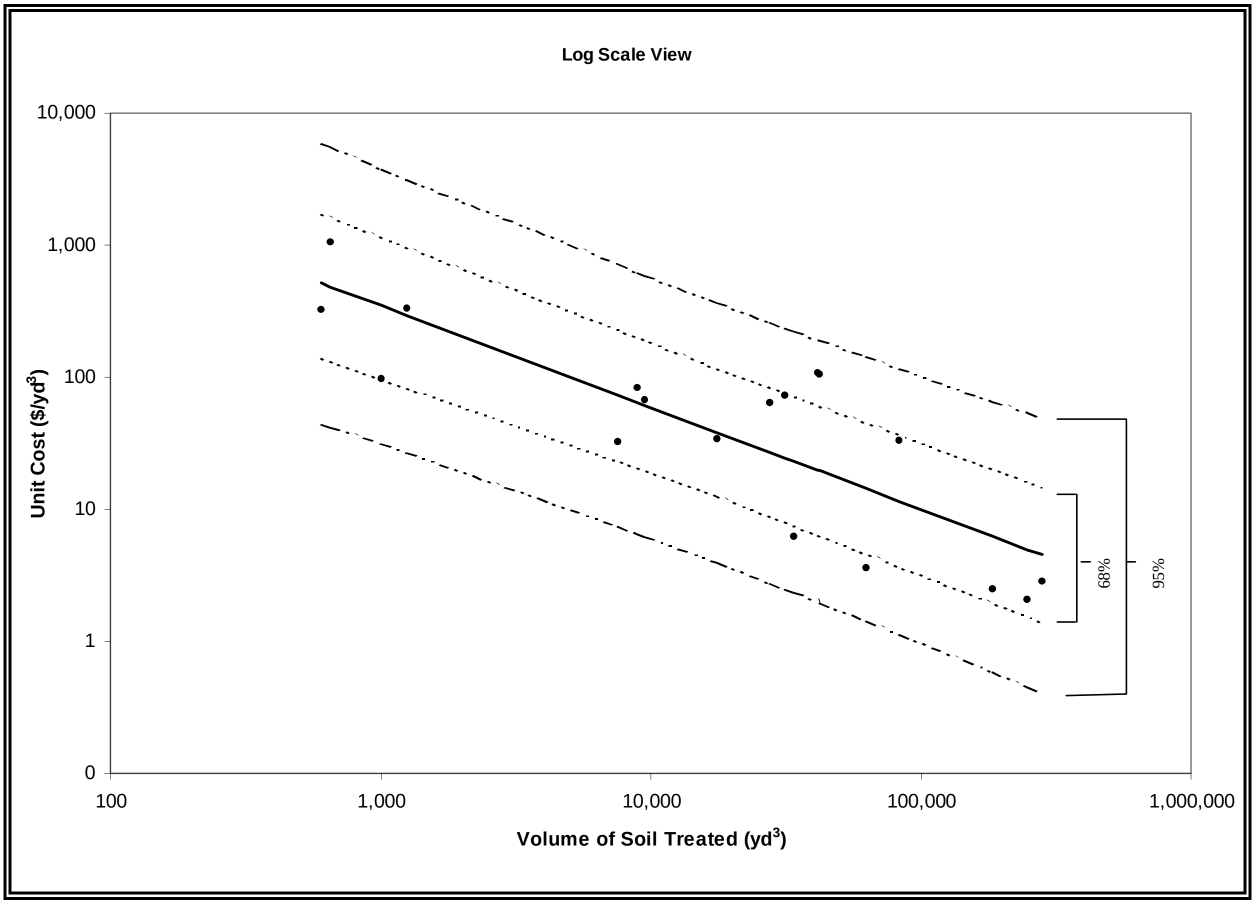
Mean	-4.9e-16
Std Dev	0.7496972
Std Err Mean	0.1767034
upper 95% Mean	0.3728045
lower 95% Mean	-0.372805
N	18
Sum Wgts	18
Sum	-8.9e-15
Variance	0.5620339
Skewness	-0.121837
Kurtosis	-0.999628
CV	-1.53e+17

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.978610	0.9237

Exhibit B-3. Soil Vapor Extraction Projects – Unit Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)



Notes:

[1] The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 18 soil vapor extraction projects are shown in the plots above.

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the line of best fit is 69 percent.

Detailed Calculations for Soil Vapor Extraction – Unit Cost vs. Volume Treated

Linear Fit

log(Cost/CY) = 11.169826 - 0.769932 log(CY)

Summary of Fit

RSquare	0.691274
RSquare Adj	0.671979
Root Mean Square Error	1.043341
Mean of Response	3.657401
Observations (or Sum Wgts)	18

Analysis of Variance

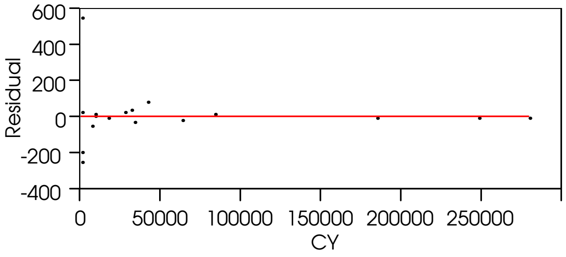
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	38.998725	38.9987	35.8260
Error	16	17.416973	1.0886	**Prob > F**
C. Total	17	56.415698		<.0001

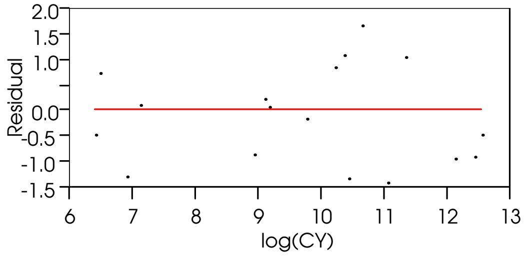
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11.169826	1.278973	8.73	<.0001
log(CY)	-0.769932	0.128633	-5.99	<.0001

Fit Measured on Original Scale

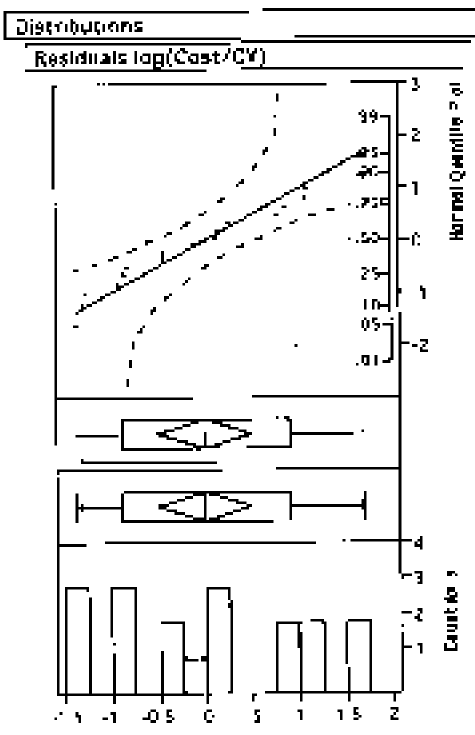
Sum of Squared Error	431701.73
Root Mean Square Error	164.26003
RSquare	0.5830949
Sum of Residuals	381.8575





Distributions

Residuals log(Cost/CY)



Quantiles

100.0%	maximum	1.6972
99.5%		1.6972
97.5%		1.6972
90.0%		1.600[illegible]
75.0%	quartile	0.9062
50.0%	median	-0.5125
25.0%	quartile	-0.8856
10.0%		-1.3122
2.5%		-1.3844
0.5%		-1.3844
0.0%	minimum	-1.3844

Moments

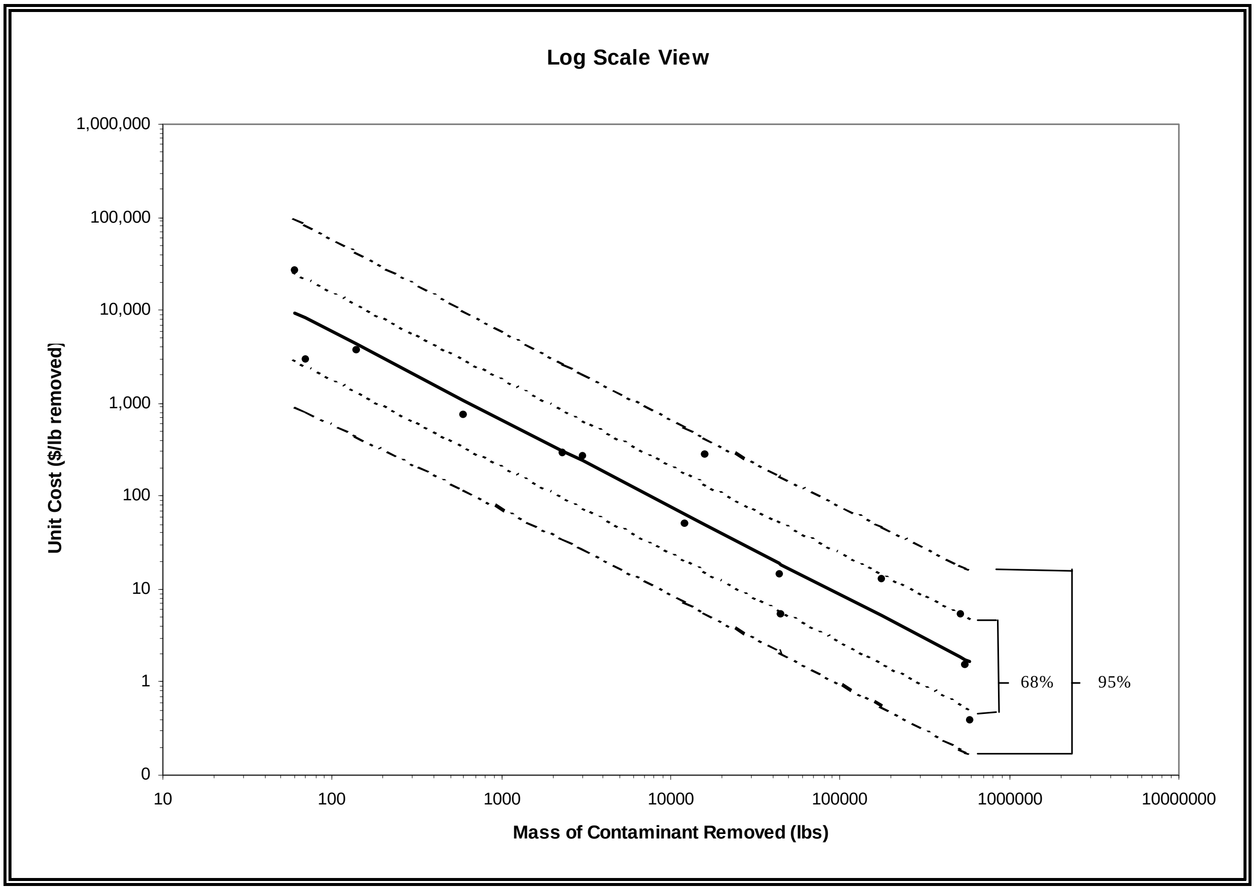
Mean	-1.5e-15
Std Dev	1.0121896
Std Err Mean	0.2385734
upper 95% Mean	0.50334[illegible]
lower 95% Mean	-0.503[illegible]
N	18
Sum Wgts	18
Sum	-2.8e-14
Variance	1.0245779
Skewness	0.2635939
Kurtosis	[illegible]1525
CV	-6.5[illegible]e-16

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.94[illegible]4[illegible]6	0.2661

Exhibit B-4. Soil Vapor Extraction Projects – Unit Cost vs. Mass of Contaminant Removed (with 95- and 68-Percent Confidence Intervals)



Notes:

[1] The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 14 soil vapor extraction projects are shown in the plots above.

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the line of best fit is 92 percent.

Detailed Calculations for Soil Vapor Extraction – Unit Cost vs. Mass of Contaminant Removed

Linear Fit

log(Cost/MCR) = 13.014916 - 0.9418857 log(MCR)

Summary of Fit

RSquare	0.919495
RSquare Adj	0.912787
Root Mean Square Error	0.957782
Mean of Response	4.42804
Observations (or Sum Wgts)	14

Analysis of Variance

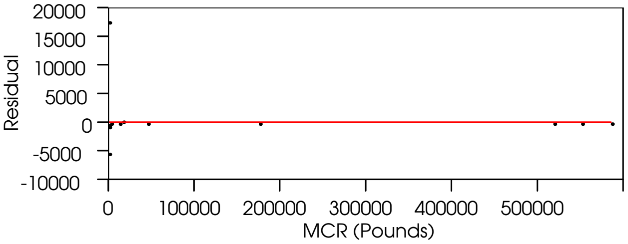
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	125.73136	125.731	137.0599
Error	12	11.00816	0.917	**Prob > F**
C. Total	13	136.73952		<.0001

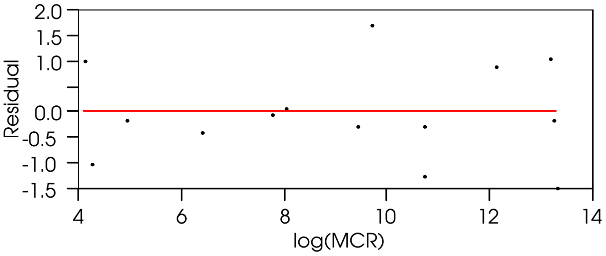
Parameter Estimates

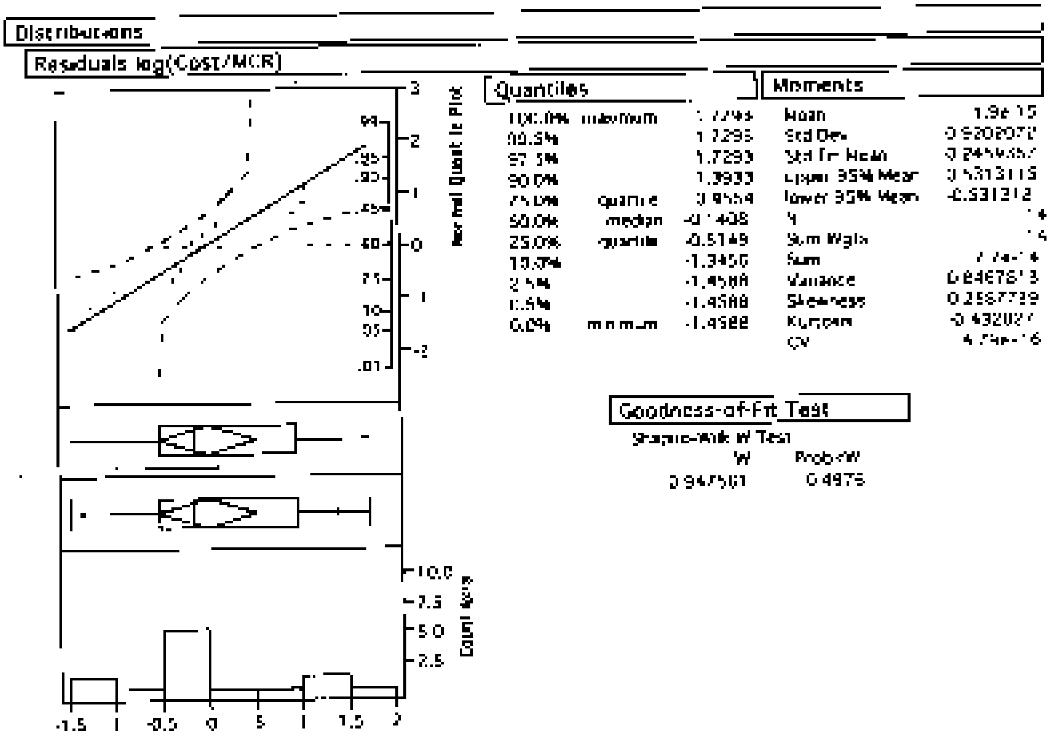
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	13.014916	0.776851	16.75	<.0001
log(MCR)	-0.941886	0.080453	-11.71	<.0001

Fit Measured on Original Scale

Sum of Squared Error	335635185
Root Mean Square Error	5288.6292
RSquare	0.4959219
Sum of Residuals	11695.193







Quantiles

100.0%	maximum	1.7293
99.5%		1.7293
97.5%		1.7293
90.0%		1.3933
75.0%	quartile	0.9554
50.0%	median	-0.1408
25.0%	quartile	-0.5149
10.0%		-1.3450
2.5%		-1.4588
0.5%		-1.4588
0.0%	minimum	-1.4588

Moments

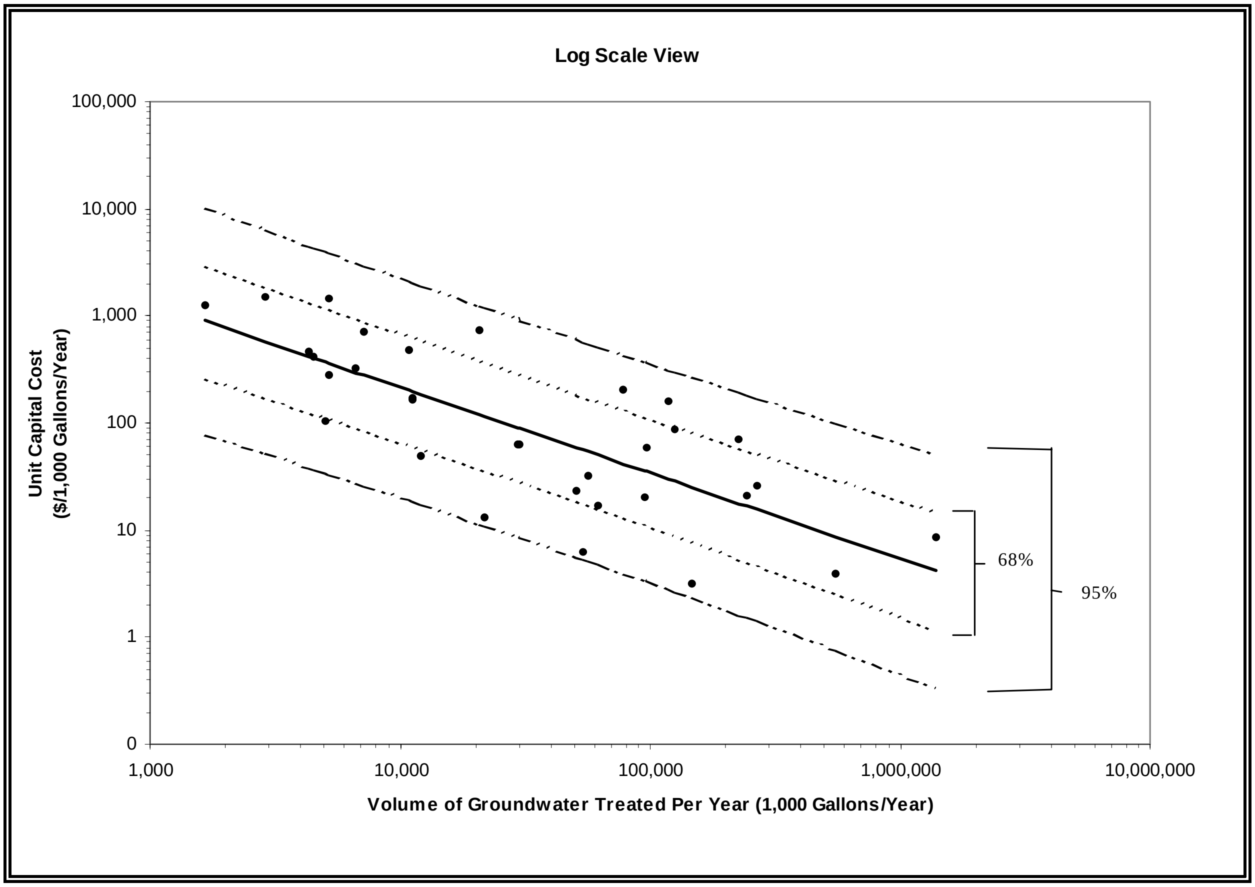
Mean	1.9e-15
Std Dev	0.9202072
Std Err Mean	0.2459457
Upper 95% Mean	0.5313115
Lower 95% Mean	-0.531312
N	14
Sum Wgts	14
Sum	2.7e-14
Variance	0.8467813
Skewness	0.2567729
Kurtosis	-0.432027
CV	4.74e-16

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.947561	0.4975

Exhibit B-5. Pump and Treat Projects – Unit Capital Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)



Notes:

1 The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 32 pump and treat projects are shown in the plots above.

2 All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

3 The coefficient of determination (r^2) for the line of best fit is 59 percent.

Detailed Calculations for Pump and Treat – Unit Capital Cost vs. Volume Treated per Year

Linear Fit

log(Unit Cost) = 12.712083 - 0.7974345 log(Volume)

Summary of Fit

RSquare	0.592322
RSquare Adj	0.578733
Root Mean Square Error	1.126549
Mean of Response	4.457747
Observations (or Sum Wgts)	32

Analysis of Variance

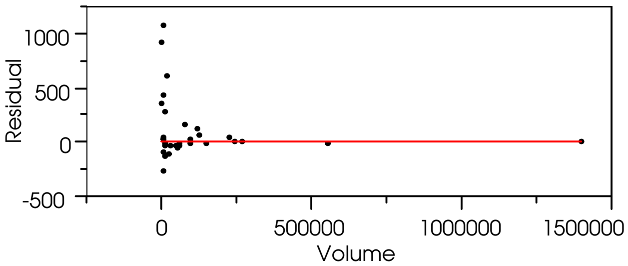
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	55.317415	55.3174	43.5875
Error	30	38.073364	1.2691	**Prob > F**
C. Total	31	93.390778		<.0001

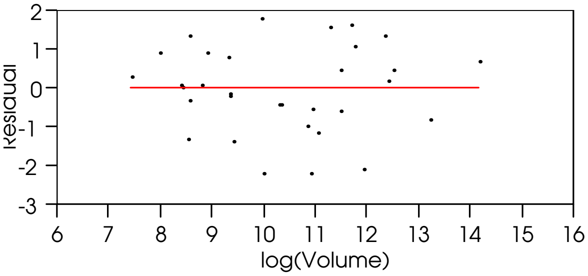
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	12.712083	1.266024	10.04	<.0001
log(Volume)	-0.797434	0.120785	-6.60	<.0001

Fit Measured on Original Scale

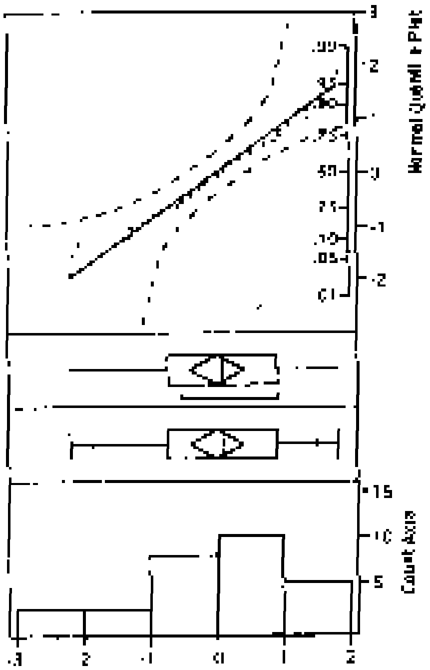
Sum of Squared Error	2908234.8
Root Mean Square Error	311.35375
RSquare	0.455782
Sum of Residuals	3311.8483





Distributions

Residuals log(Unit Cost)



Quantiles

100.0%	maximum	1.8156
99.5%		1.8156
97.5%		1.8156
90.0%		1.5254
75.0%	quartile	0.9153
50.0%	median	0.0700
25.0%	quartile	-0.7389
10.0%		-1.8427
2.5%		-2.1853
0.5%		-2.1853
0.0%	minimum	-2.1853

Moments

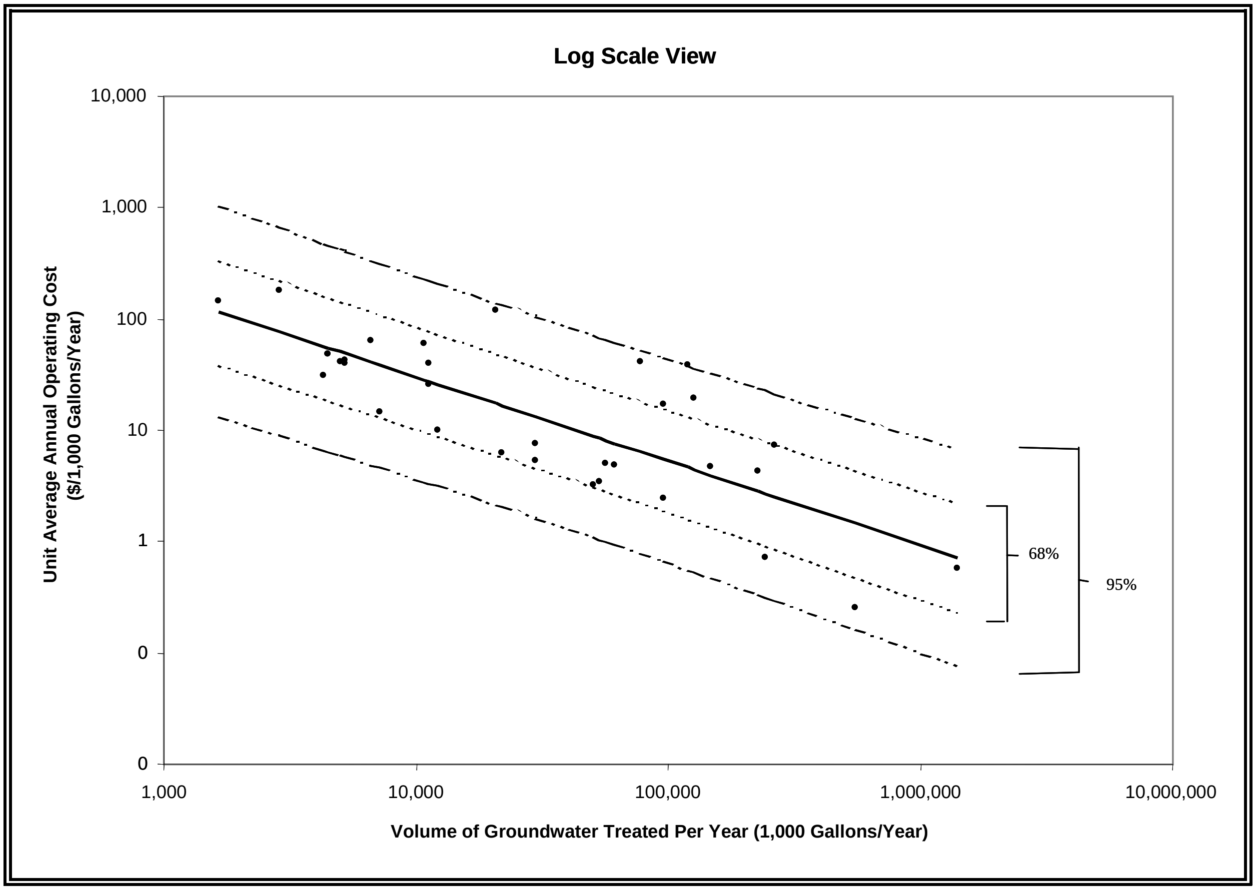
Mean	2.1e-17
Std Dev	1.1082297
Std Err Mean	0.1959092
upper 95% Mean	0.3995566
lower 95% Mean	-0.399557
N	32
Sum Wgts	32
Sum	6.7e-16
Variance	1.228173
Skewness	-0.312355
Kurtosis	-0.528556
CV	5.37e+18

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.953553	0.1992

Exhibit B-6. Pump and Treat Projects – Unit Average Annual Operating Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)



Notes:

[1] The line of best fit (solid line) and 68- and 95-percent confidence limits (dashed lines) for individual predicted points for 32 pump and treat projects are shown in the plots above.

[2] All reported costs were adjusted for location and years during which costs were incurred, as described in the text.

[3] The coefficient of determination (r^2) for the line of best fit is 62 percent.

Detailed Calculations for Pump and Treat – Unit Average Annual Operating Cost vs. Volume of Groundwater Treated per Year

Linear Fit

log(Unit Cost) = 10.356779 - 0.754574 log(Volume)

Summary of Fit

RSquare	0.619322
RSquare Adj	0.606633
Root Mean Square Error	1.00739
Mean of Response	2.546098
Observations (or Sum Wgts)	32

Analysis of Variance

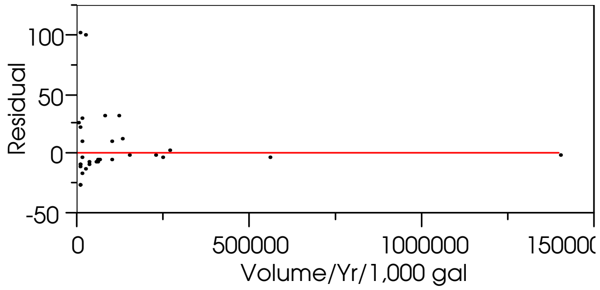
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	49.530820	49.5308	48.8068
Error	30	30.445034	1.0148	**Prob > F**
C. Total	31	79.975854		<.0001

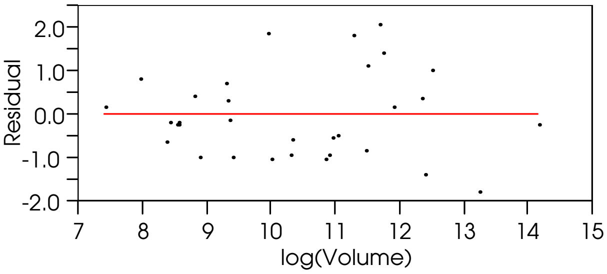
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	10.356779	1.132112	9.15	<.0001
log(Volume)	-0.754574	0.108009	-6.99	<.0001

Fit Measured on Original Scale

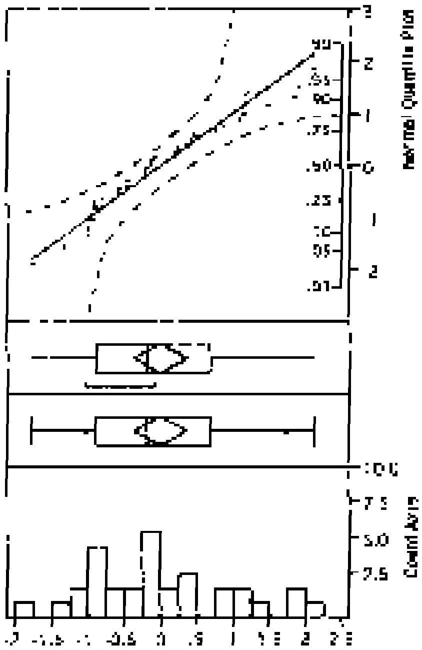
Sum of Squared Error	28362.686
Root Mean Square Error	30.747729
RSquare	0.5065955
Sum of Residuals	255.52333





Distributions

Residuals log(Unit Cost)



Quantiles

100.0%	maximum	2.1204
99.5%		2.1204
97.5%		2.1204
90.0%		1.7334
75.0%	quartile	0.6847
50.0%	median	-0.1793
25.0%	quartile	-0.8617
10.0%		-1.0130
2.5%		-1.7636
0.5%		-1.7636
0.0%	minimum	1.7636

Moments

Mean	2.4e-15
Std Dev	0.9910085
Std Err Mean	0.1751873
upper 95% Mean	0.3572942
lower 95% Mean	-0.357294
N	32
Sum Wgts	32
Sum	7.7e-14
Variance	0.9820974
Skewness	0.5520105
Kurtosis	0.36083
CV	4.12e+16

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.957171	0.2011

Response to External Reviewer Comments on the Statistical Details of the "Remediation Technology Cost Compendium – Year 2000"

The following are responses to some of the external reviewer comments on the report.

1. Providing optimal fits for essentially non-linear models can be an exhaustive exercise. Most statisticians frown on using exploratory techniques for non-linear modeling; that is, one should have some idea of the correct functional form that best describes the data. In our case, our assumption that the cost data are described by a negative exponential model is probably pretty sound. A logarithmic transformation was used to linearize the data, and for several data sets a linear regression of the transformed data provided a reasonable fit. The reviewers are correct, however, that the fit was very poor for some data sets. An additional concern regarding the normality of the residuals led them to suggest we use Box-Cox power transformations to find an optimal transformation for each data set. This is a good suggestion, but is only one of many things that could be done to find the best fit to the data. Another approach worth exploring is using breakpoint regression (or other more sophisticated regressions techniques), which allows you to fit more than one regression model to each data set. This level of effort is only warranted if you are interested in providing optimal predictive models. A full discussion of estimation errors associated with the regression approach we used could be provided at a separate time.

2. The reviewers implied that the Shapiro-Wilk W test has low statistical power to correctly identify departure from normality when sample sizes are small. This is true, and is one reason why histogram and box-plots, normal quantile plots, and summary tables of quantiles and moments for the residuals for each plot are provided. If text is added to the report to better interpret the statistical output and to concisely summarize the main limitations of the approach, then this should satisfy the more sophisticated readers.

3. The report provides summary graphics of the fits for each data set in the main body, but the salient statistical details one needs to evaluate each regression model are buried in the appendix. This obviously has advantages and disadvantages. In order to not mislead readers into thinking that these are robust predictive models, it might be a good idea to provide a very clear explanation of the objectives and limitations of the approach used in the front of the report. Also, a few corrections and additions to the "Notes" section below each figure might help to clarify things (e.g., r^2 is the coefficient of determination).

4. The reviewers are correct in pointing out that text needs to be added to explain the confidence intervals (CI) that are shown in the plots. Graphical and tabular results for CIs for both the regression line (i.e., per unit cost - a random variable) and for the expected per unit cost (our predicted dependent variable) for individual values of the independent variable (our "wide" CIs) are provided. Since the report identifies CIs for individual predicted points, the reviewer is correct in saying that we would need to calculate joint confidence bounds based on Schwartz's inequality if we want to correctly report the significance level for any combined statements made regarding more than one per unit cost.

APPENDIX C
Active Members of the FRTR Ad Hoc Work Group on Cost and Performance

Listed below are members of the Work Group who participated in efforts to collect cost and performance data.

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